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A SEDIMENTATION MODEL FOR THE DEPOSITION OF GLACIGENIC DEPOSITS IN CENTRAL
ALBERTA

by

JOHN JOSEPH KULIG

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH
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ABSTRACT

Detailed sedimentological analysis of glacial sediments, previously identified as tills, exposed along the Battle River in central Alberta, has led to their reinterpretation as waterlain diamictons deposited in front of an ice sheet grounded in a shallow proglacial lake. Thirteen facies were identified in the study area but only seven are crucial to the development of the sedimentation model. These seven facies are found in two facies associations (1) a diamicton-rhythmic couplet association and (2) a silt bed-rhythmic couplet association. Within the diamicton-rhythmic couplet facies association there are two sequences. The first begins with facies 6 (unstratified diamicton) and passes through facies 8 (intercalated sand laminae and diamictons with large clasts), facies 9, (intercalated diamicton, silt laminae, and large clasts), facies 10, (interbedded diamicton and silt layers) and culminates in facies 13, (rhythmic couplets). The second sequence differs from the first solely in its initial facies, facies 7, (coalesced lensoid-shaped diamictons with agglomerated texture). The silt bed-rhythmic couplet facies association consists of facies 12, (silt beds composed of graded silt laminae and minor clay interbeds) which is conformably overlain by facies 13, (rhythmic couplets).

In the grounded ice scenario, large volumes of sediment are released at the grounding line by: undermelting the ice margin (forming subaquatic debris banks), brash ice calving (contributing dropstones and diamicton pellets), influx of sediment-charged streams (depositing sand, silt, clay), and subaerial and/or subaqueous sediment flows (depositing diamictons). The resulting deposit is oversteepened, oversaturated, has high pore-pressures, and is therefore prone to failure, causing redistribution of debris from the subaquatic debris banks into the proximal area of the lake basin. Distally in the lake basin turbidite deposits are emplaced. High initial sedimentation rates result in frequent flowage of the subaquatic debris bank sediments depositing a massive-appearing diamicton (facies 6). As the interval between flowage events increases, sufficient time is available for proximal turbidites to deposit sands on, and for bottom currents to winnow the upper surfaces of the diamictons forming the sand laminae of facies 8. In areas of the ice margin where there is limited disturbance of the water between sediment flow events, massive silts are interbedded with diamictons (Facies 7). Further in the lake basin turbidites deposit silt laminae between thin diamictons, (facies 9), while still further within the lake

distal turbidite deposits are emplaced (Facies 12 and 13). Retreat of the ice margin results in superposition of basinal facies (facies 9, 12, and 13) over proximal facies (facies 6, 7, and 8), and accumulation of thick beds of graded silt laminae and rhythmic couplets (facies 12 and 13). These deposits are also prone to failure resulting in the formation of diamictons with high volumes of laminated silt and clay intraclasts which are interbedded with beds of graded-silt laminae (Facies 10). Renewed retreat of the ice margin permits the deposition of rhythmic couplets (facies 13) which are the final facies in the diamicton-rhythmic couplet facies association.

PREFACE

There are two things that amaze me about my thesis. First, that research expenses over four years were less than \$4,000.00! So research can still be done on a shoestring budget in these days of high interest rates and deficit financing (maybe we shouldn't let NSERC know). Secondly, I am amazed that the thesis is finally finished. It seemed like it was going to last forever. This brings to mind a Chinese proverb which I learned in my Mandarin class (credit for instilling in me any ability to read and write Mandarin Chinese goes to Dr. Lin):

不畏慢
只怕不前

which translates to be:

Don't be afraid of slowness.

Just be afraid of standing still.

At times it really seemed like I was standing still.

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I. INTRODUCTION

A. INTRODUCTION

In recent years emphasis in glacial geology has shifted from stratigraphic correlation of "till" units to genetic interpretation of glacial deposits thereby explaining the vertical and lateral variations in these deposits as reflections of changes within the sedimentological processes which deposited them. Identification of the facies present in the deposits is based on their primary sedimentological characteristics. The development of facies models which account for the spatial and temporal variations of the facies within an area is of primary importance in understanding variations within assemblages of glacial deposits and in extending the interpretations from one area to another. This thesis uses a facies approach to interpret the glacial deposits in the Wetaskiwin area of central Alberta and to generate a facies model which accounts for their lateral and vertical variations and which can be used to interpret similar deposits in other areas.

B. OBJECTIVES

The objectives of this study are:

1. to identify the facies present in the glacial sediments,
2. to determine the environments of deposition of the facies present
3. to formulate a sedimentation model which explains the lateral and vertical changes of these facies.
4. to develop a late Pleistocene geologic history of the study area
5. to discuss the implications of this study to the interpretation of similar deposits in other areas
6. to suggest areas in the field of glacial sedimentology which require further research.

C. LOCATION AND PHYSICAL SETTING

The study area is located in central Alberta 15 kilometers east of Wetaskiwin (Fig.

1.1). The terrain is generally flat to slightly rolling except for a narrow band of moderate to high relief hummocky terrain (Fig. 1.2) and a zone of irregular hillocks in the vicinity of Bittern Lake (Fig. 1.2). The Battle River flows north and east through the study area.

Figure 1.1 Location of the study area. Blowup of the study area is located in the circle.

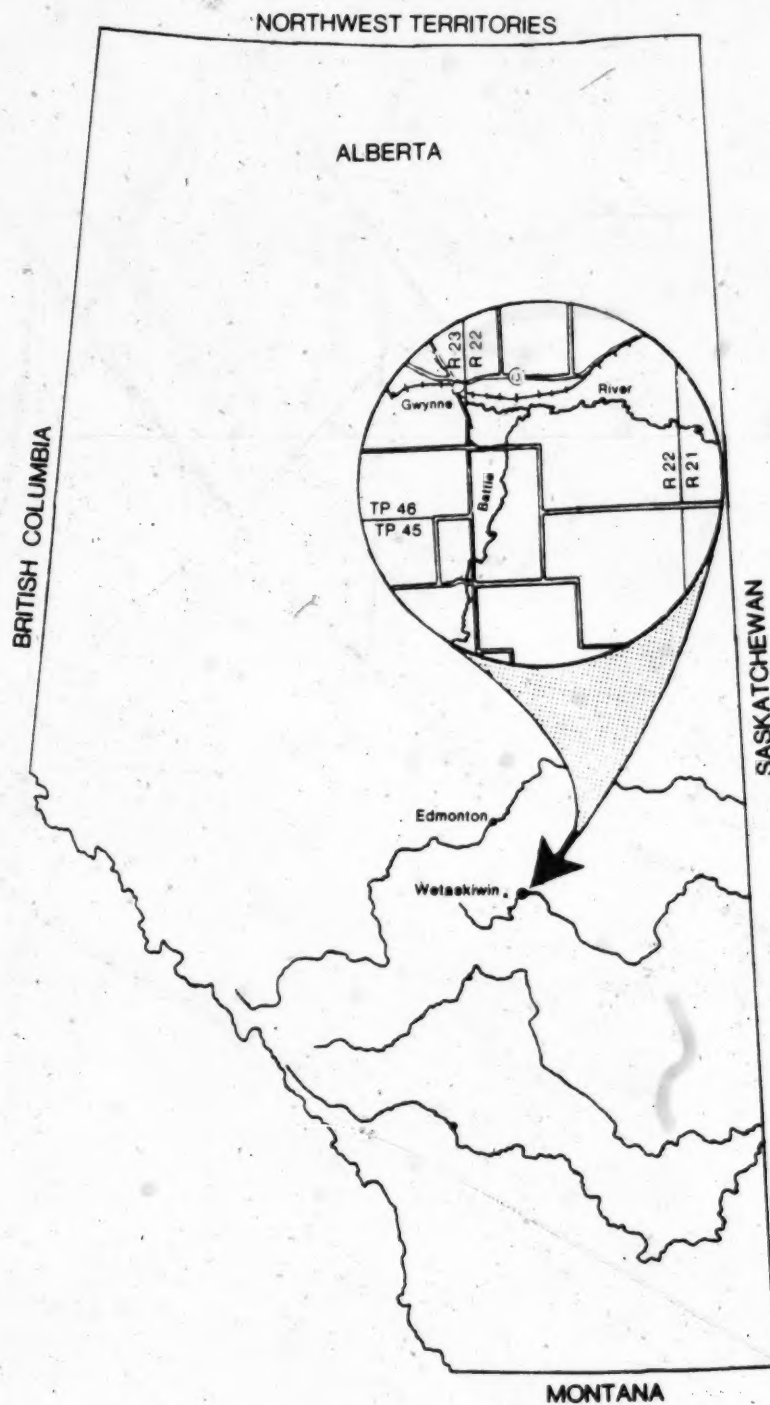
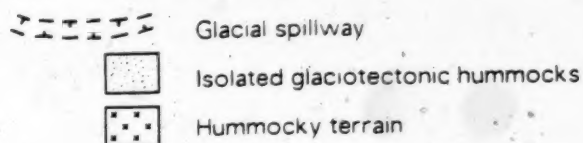
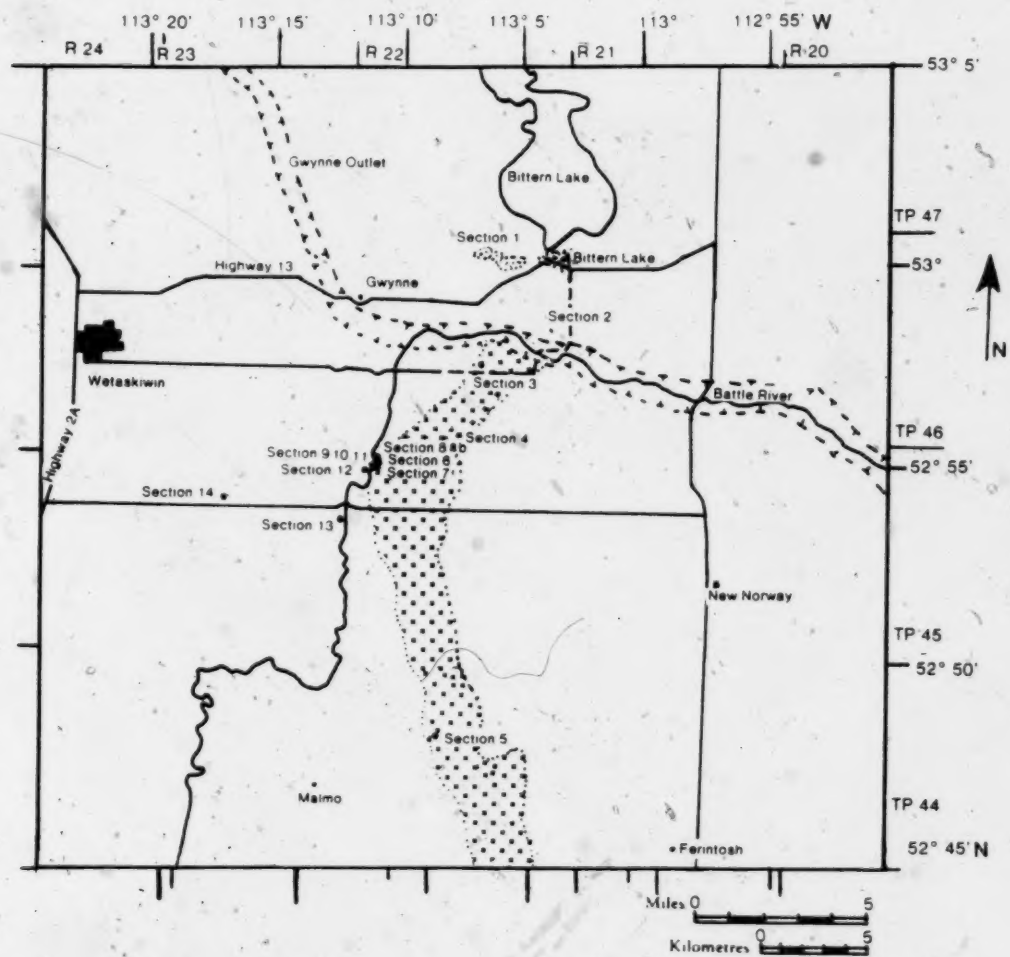


Figure 1.2 Location of the sections within the study area and the areas of hummocky terrain.



Section 1	Highway 13 roadcuts
Section 2	Delta Pit Site
Section 3	Ridge Section 1
Section 4	Ridge Section 2
Section 5	Hummocky Sand Pit
Section 6	Riverbend 1 (RB1)
Section 7	Riverbend 2 (RB2)
Section 8a,b	Main Section (a) Kettle Section (b)
Section 9	New Pit South (NPS)
Section 10	New Pit North (NPS)
Section 11	New Pit West (NPW)
Section 12	Old Pit (OP)
Section 13	Farbridge Section (FS)
Section 14	West Pit Section (WPS)



entering the Gwynne Outlet, a glacial spillway, near the town of Gwynne from where it continues eastward as an underfit river.

Local bedrock is comprised of the Upper Cretaceous Horseshoe Canyon Formation of the Edmonton Group (Gibson, 1977). The bentonitic sandstone and shale beds of this formation contain discontinuous coal seams and dip gently (1 to 2 degrees) to the west. The subsurface bedrock topography is a badlands type (Tedder, 1982).

Prior to glaciation, the Red Deer River flowed through the study area in a 20 km wide valley, depositing sands and gravels unconformably on the bedrock. These gravel deposits range from a trace to 10 m in thickness and are composed of well rounded Rocky Mountain-derived quartzite and sandstone clasts and are devoid of clasts originating from the Canadian Shield (Stalker, 1960; Tedder *et al.*, 1982). The onset of the last glaciation, from the northeast, deflected the Red Deer River south and east around the terminus of the ice sheet (Warren, 1944; Gravenor and Bayrock, 1956). This deflection caused the abandonment of its former river valley which was infilled by the sediments of the last glaciation and through which the Battle River has incised (Gravenor and Bayrock, 1956).

D. PREVIOUS RESEARCH

Glacial deposits of the study area vary from a trace to 40 m in thickness and lie unconformably on the bedrock and pre-glacial sands and gravels (Tedder *et al.*, 1982). Warren (1954) briefly described glacial deposits of the area identifying a lower gray till and an upper brown silt till. Warren (1937) named the high relief hummocky terrain of the study area the Buffalo Lake Moraine and stated that it marked the terminus of the Mid-Wisconsinan glacial advance in central Alberta. It is generally accepted today that Mid-Wisconsin time was not marked by an extensive ice advance in western Canada. Stalker (1960) identifies an old till (Labuma or Maunsell) separated from a younger till (Buffalo Lake) by a sand and gravel layer. Subsequent investigation within the study area was confined to a gravel inventory (Shetson, 1976) and a damsite feasibility study which intensively investigated the engineering properties and thickness of the glacial sediments (Tedder *et al.*, 1982). Boreholes drilled by the Alberta Research Council in, 1983 revealed displaced slabs of bedrock encased by till (Shetson, 1983, personal

communication).

No reliable stratigraphic correlation of the units in the study area has been made but research on the Cooking Lake Moraine (Emerson, 1977; Jennings, 1984), a northern extension of the Buffalo Lake Moraine, east of Edmonton is useful in establishing a time frame for the Buffalo Lake Moraine. Emerson (1977) determined that the deglaciation of the Cooking Lake Moraine occurred between 11,000 and 9,000 years BP. Jennings (1983) identified two tills separated by lacustrine sediments. Shells within these lake sediments gave a $26,000 \pm 1100$ years BP radiocarbon date. He concluded that the till above the lake sediments was mostly of sediment-flow origin and had undergone several cycles of relief inversion, forming the hummocky terrain by the processes described by Gravenor and Kupsch (1959) and Parisek (1970). The glacial sediments of the study area relate to the upper till of Jennings (1984) and represent a time period of 11,000 to 9,000 BP based on his correlation to Stages 3 and 4 of St-Onge (1972).

Investigation on the sequence of glacial lakes in central Alberta also aids in bracketing the age of the deposits as well as providing information on the areal extent of the lakes in the study area. Stalker (1960) discusses a 10-stage deglaciation sequence for the Stettler map sheet during which numerous glacial lakes formed and drained. The glacial lakes which existed in my study area were present during his Stages 9, 10, and 11 during which times the elevation of the spillways was 2,700 ft. (823 m, Phase 9), 2,600 ft. (792 m, Phase 10) and 2,500 ft. (762 m, Phase 11). St-Onge (1972) discusses a seven-stage sequence of appearance and drainage of late Wisconsinan glacial lakes in central Alberta. The elevation of the outlets of these lakes are 2,700 ft. (823 m) for glacial lake Leduc, 2,600 ft. (792 m) for glacial lake Malmo, and 2,500 ft. (762 m) for glacial Lake New Norway. He concluded that Stages Two through Seven spanned the 13,500 to 11,400 years BP time period. Glacial lakes Leduc, Malmo, and New Norway, which covered the study area, were in existence during Stages 3 and 4 of St-Onge (1972), bracketing them between these two dates. The two chronologies of glacial lake drainage (Stalker, 1960; St-Onge, 1972) closely correspond to each other.

II. METHODS OF INVESTIGATION

A. FIELD METHODS

Prior to fieldwork air photographs were examined to determine the general geomorphology of the study area and the probable location of suitable sections exposed in rivercuts, gravel pits, and roadcuts (Fig. 2). They were investigated over the course of two field seasons, May - September 1982, April, and September to November, 1983. During the first field season the fieldwork, consisting of detailed descriptions and sampling, supplemented by photographs, was concentrated on the Main, Riverbend 1 and 2, and Far Bridge sections. During the following field season, several new sections were located. Of these, work was concentrated in the New Pit sections (located directly west and across the Battle River from the Main and Riverbend sections) as these exposures were fresh, almost completely exposed, accessible, easy to work, and in close proximity to the Main, Riverbend 1 and 2, and Old Pit sections, facilitating correlation of the sedimentary units between sections.

The sedimentary units in the New Pit sections were identified, described, photographed, and sampled. Samples consisted of bulk textural samples, pebble samples, and oriented blocks for the production of oriented thin sections (Production of oriented thin sections from blocks of unconsolidated sediment is discussed in Appendix 2). In addition six macrofabrics were measured in the New Pit sections. The location and type of samples obtained are shown in figures A 1.1 to A 1.8 in Appendix 1.

Once the stratigraphic sequence was established, the other sections in the field area were described, photographed, and sampled. Fewer samples were collected in the other sections as the stratigraphy of these sections was similar to that observed in the New Pit sections. The decision was made at this time to base the thesis on the interpretation of sedimentary features and to use textural analysis as a supplement to the sedimentary features. Textural and pebble lithology samples, oriented blocks, and macrofabrics were obtained from the Main, Riverbend 1, Old Pit, and the New Pit sections and used to test specific hypotheses on the the genesis of the deposits.

B. LABORATORY WORK

Textural samples were analyzed using the hydrometer method specified in ASTM D422(1963) and sieved following the procedures given in ASTM D423(1963). The particle size distributions were plotted on probability paper and the grain size parameters were calculated using the formulas and procedures given in Folk and Ward (1957) and Folk (1966).

Pebble samples from the New Pit West and Riverbend 1 sections were sorted into >1.5 and <1.5 cm categories. The clasts in these categories were identified lithologically and grouped into local bedrock, western carbonates, mountain lithologies, eastern carbonates, and Canadian Shield lithologies. These lithologic groups were transformed into pebble lithology indices using the formulas detailed in Shetson (1983, 1984). The results were tabulated (Table---) and plotted (Figure ---). A detailed explanation of this method is given in Appendix 3.

THIN SECTIONS

Thin sections for microscope analysis and microfabric determination were made from oriented blocks obtained from the New Pit, Main, Old Pit, and Riverbend 1 sections. The oriented blocks were impregnated with casting resin, then cut into $2 \times 3 \times .5$ inch blocks. These were mounted on glass slides and thin sections produced using a logitech automatic thin section machine. A detailed procedure for the manufacture of thin sections from unconsolidated materials is given in Appendix 2.

FABRIC DATA

MACROFABRICS

Macrofabrics were measured in the New Pit, Riverbend 1 Old Pit, and Gully sections. Andrews and King (1969) demonstrated that a sample size of 25 is sufficient to establish whether a statistically valid clast fabric is present and that measurement of several fabrics in close proximity provides more data than a single pebble fabric with a large sample size. Macrofabrics were determined using sample sizes of 25 to 35 clasts. The clasts were > 2.5 cm in length and had a:b axial ratios of at least 2:1 (prolates in the Zingg classification system (Zingg, 1933). Macrofabrics were measured primarily in the

thicker massive diamicton units. Some diamicton layers were too thin to obtain macrofabrics from a single layer. In such cases macrofabrics were measured above and below a conspicuous marker bed from a restricted area of the unit but covering several diamicton layers. To obtain fabric information from individual layers microfabrics were measured from thin sections cut parallel to bedding from individual layers.

MICROFABRIC SAMPLES

The microfabric data was obtained from the thin sections by using a projecting microscope to project the oriented thin section onto a sheet of paper. The orientation and scale of the thin section was transferred to the paper. Elongate grains with length-width ratios of at least 2:1 were used in the determinations. These grains varied from 0.2 to 2.3 mm in length. After the grain orientations were plotted on paper the resulting grain orientation map was digitized for computer processing using a program developed by D.N. Proudfoot, Department of Geology, University of Alberta which enters the orientations of the grains directly into the computer. The orientations of the clasts are then computed using the Run:Orient program developed by H.A.K. Charlesworth, Department of Geology, University of Alberta. The eigenvectors are an indication of the dominant orientation of the clasts while the eigenvalues give an indication of the strength of the eigenvectors. As the degree of bi- and multi-modality of the fabric set increases, the size of the eigenvalue decreases. Eigenvalues below the strength of 0.5 indicate a random orientation between 0.5 and 0.8 the orientation is weak but statistically significant; and over 0.8 the orientation is strongly developed (Mark, 1973, 1974; May, 1977). Evaluations of the validity of the trend produced can be made. The degree of bi- and multi-modality is important as the eigenvector determined from the data is an average of all the trends in the data and if there are two or more strongly developed modes the resultant eigenvector is an intermediate value between these modes and does not represent the true orientation of the clasts within the deposit (Mark, 1973, 1974; Humlum, 1981). Rose diagrams produced by the program allow a visual estimate of the degree of bi- and multi-modality of the data to be made.

USE OF THE SCANNING ELECTRON MICROSCOPE

The scanning electron microscope was used to observe the microstructure of several samples to indicate the degree of shearing within the deposit. Observations were made as to the presence or absence of alignments of fine particles near larger grains and whether the samples had open cardhouse structures or closed microstructures.

III. DEPOSITION IN GLACIAL ENVIRONMENTS: AN OVERVIEW

Modern process studies and detailed sedimentological investigations have only recently begun to understand the variability in glacial deposits.

For the purposes of this thesis glacial deposits have been placed into five major categories:

1. glaciofluvial deposits associated with stagnant ice deposits and proglacial outwash plains,
2. glaciotectionic deposits
3. tills formed and deposited directly by glaciers and ice sheets,
4. debris flow assemblages associated with stagnant ablating ice,
5. subaquatic sediment assemblages formed in glaciolacustrine and glaciomarine settings by processes ranging from sediment flows, calving ice, undermelting of floating ice, and turbidity currents

Glacial assemblages are seldom composed of sediments deposited within a single glacial environment or by a single depositional process but represent complex deposits of several environments and processes. Many processes are active within each environment resulting in the deposition of a wide range of sediments. As deposits of one category can be deposited in direct association or totally within those of another category, assigning a sediment to a specific category often depends upon the context of the total sediment assemblage. Diamictic deposits are the most problematical as meltout tills, lodgement tills, subaqueous sediment flows, and subaerial sediment flows, despite formation by different processes commonly possess similar sedimentary characteristics. Only detailed analysis of the sediments and their context within the total sediment assemblage will permit correct interpretation of these diamictic deposits. Other processes such as glaciotectionism, glaciofluvial deposition, and turbidity currents deposit sediments which are distinct and more readily associated with a specific depositional process or environment of formation. To provide a background for the discussion and interpretation of the facies to be presented in the following chapters, specific aspects of glacial sedimentary processes and the sedimentary features which are associated with them will be reviewed. Emphasis has been placed on processes which produce sedimentary structures which are similar to those observed in the glacial deposits of the study area.

A. GLACIOFLUVIAL SEDIMENTATION

Glaciofluvial sediments are the product of flowing water and therefore have the characteristics of normal fluvial sediments. Only by their close association, areally or in stratigraphic sections, with obvious glacial sediments can they be identified as glaciofluvial. Since these deposits are readily classified and have been amply described in the literature they will not be reviewed here. Detailed reviews of glaciofluvial sedimentation are given by Jopling (1976), and Church and Gilbert (1976). Common ice contact glaciofluvial deposits such as eskers and kames, were reviewed by MacDonald and Banerjee (1971), Banerjee and MacDonald (1976).

B. FORMATION OF GLACIOTECTONIC FEATURES

The ability of ice sheets to fold, pluck, and carry bedrock rafts and deposit them intact or comminuted is well documented (Stalker, 1965; Weertman, 1967; Moran, 1971; Clayton and Moran, 1974; Christensen and Whitaker, 1976; Moran *et al.*, 1980; Fenton, 1983). In some cases unconsolidated materials have also been entrained by the ice and redeposited (Moran, 1971; Moran *et al.*, 1980; Shaw, 1972). *In situ* deformation of the underlying substrata is also common (Kupsch, 1961; Moran *et al.*, 1980; Fenton, 1983). Ice thrusting is usually associated with the upslope edges of uplands and ice marginal positions (Clayton and Moran, 1974; Moran *et al.*, 1980). Thrusting usually occurs in a narrow (<5km) frozen bed zone at the margin of the ice sheet where the flow lines are diverging (Clayton and Moran, 1974). At the frozen margin, water from the ice sheet interior is unable to escape, creating high pore water pressures within the substrate which decreases the substrate shear strength, allowing it to be carried into the ice along the diverging flow lines (Clayton and Moran, 1974; Christiansen and Whitaker, 1976). Once entrained into the englacial zone of the ice sheet, the material is, for the most part, carried passively. Deposition occurs when the ice becomes inactive or when debris overloaded ice is sheared-off and deposited beneath the active ice (Boulton, 1976a).

Moran *et al.* (1980) and Fenton (1983) have described the areal distributions of landforms associated with glaciotectonism. In an up-ice direction from the thrust bedrock, a pond or shallow depression of erosive origin, the source area of the blocks, usually occurs. The large blocks quarried from the depression are usually deposited

immediately down-ice from the depression (Moran *et al.*, 1980). Thrusted material originating more than 2-3 km from the ice margin is usually streamlined by glacial over-riding (Moran *et al.*, 1980). Fenton (1983) has described the formation of rubble moraine in which the size of the bedrock masses decreases down-ice from the depression due to comminution during transport. Associated with the displaced bedrock slabs are basal tills which may be injected into the bedrock or deposited in conjunction with the bedrock blocks (Christensen and Whitaker, 1976).

C. DEPOSITION OF LODGEMENT AND MELTOUT TILLS

Till, *sensu stricto*, is an unsorted, unstratified sediment deposited directly by glacial ice (Glossary of Geology 2nd. Edition, 1980, p. 653). Many genetic classification schemes have been put forth in the literature (Boulton, 1976; Dreimanis, 1976; Shaw, 1976) but none have gained universal acceptance due partly to the lack of diagnostic features for each till type and differing ideas as to the importance of specific features. Two of the major till types are lodgement and meltout tills. A third category, flow tills, which includes both subaerial and subaqueous debris flows, despite being entrenched in the glaciological literature, cannot be considered tills *sensu stricto*, as the resedimentation process by which they are formed destroys the features formed by direct glacial deposition and imprints the sediment with sedimentary features related to the debris flow process (Lawson, 1979a). Waterlain diamictos deposited by undermelting of floating ice or deposited partially from icebergs are also excluded from classification as "true" tills as settling through the water column imprints the sediments with features not resulting from direct glacial deposition.

LODGEMENT TILLS

Table 3.1 lists the common lodgement till characteristics.

Lodgement tills are formed by a "plastering-on" process. When the frictional resistance between the glacier bed and the debris in traction at the base of the ice increases to a point where the frictional drag on the particle is greater than the tractive forces the particle becomes lodged (Boulton, 1976; Shaw, 1982). Pressure melting at the points of contact with subglacial obstacles, and shearing are important secondary

Table 3.1 CHARACTERISTICS OF LODGEMENT TILLS

AUTHOR	CHARACTERISTICS
Krüger 1979	-smudges -small scale deformations of till matrix by pushed clasts -clasts possess stoss and lee sides with the lee-side ramp-shaped and pointing upice -strong consistent clast fabrics parallel or perpendicular to ice flow -glaciotectonice drag structures -lenses of sorted material plowed and distorted by movement often associated with cavities in the lee of boulders -imbricated boulders and boulder lines -boulders with smoothed upper surfaces and rough bases
Dreimanis 1976	-compact, dense -presence of shear planes marked by sand or silt laminae -fissility or foliation common -strong unimodal clast fabrics parallel to ice flow direction -local lithologies dominate
Boulton 1975, 1976	-occur at base of section -clusters of boulders -shear banding due to streaking out -well-developed fabrics, forming a consistent assemblage parallel to ice flow -isoclinal folding of lower sediments often showing shearing by ice flow -joints parallel to the surface due to unloading -associated with fluted or drumlinized terrain. -boulders imbricated upon each other
Müller 1983	-well-developed fissility -thin layers of well-sorted sediments due to dewatering or flowage of water at the base of the lodging ice -draping of clasts by silt and sand laminae -truncation of sand and silt laminae at clasts -veining and microfoliation visible in thin section -CaCO₃ deposition in lee positions giving laminations
Krüger and Marcussen 1976	-well developed fabrics, unimodal in nature -compact -slickensided sub-horizontal joints

mechanisms (Boulton, 1970a; Weertman, 1961). Lodgement tills are characterised by their fine grained texture, high density, and well-developed unimodal clast fabric (Boulton, 1978; Shaw, 1979; Kruger, 1979). Clasts of soft lithologies are streaked, smudged, and boudinaged by the lodgement process (Kruger, 1979). Flat iron-shaped cobbles and boulders, heavily striated on their upper surfaces but with unstriated bases are commonly aligned with their blunt ends pointing up-ice (Boulton, 1978; Kruger, 1979). They can also be imbricated upon each other forming stone lines (Boulton, 1978, Kruger, 1979). Syn-depositional deformational structures are also observed within the till matrix in front of clasts formed by pushing of the overriding ice (Kruger, 1979). Streaks and laminae of silt and sand within diamictons were interpreted to be formed by shearing during the lodgement process (Dreimanis, 1976; Boulton, 1976a). Müller (1983), suggests that the sand laminae may represent dewatering features formed when the structure of the sediment collapses during lodgement or be formed between lodgement episodes by winnowing at the sediment-ice interface by a thin layer of flowing water. The laminae formed by dewatering will drape clasts in the till due to differential compaction after deposition. The laminae also terminate abruptly at clasts as the clasts are points of water convergence. This water convergence also forms silt and clay layers around clasts, as observed in a modern Icelandic lodgement till (Boulton, 1976a). Müller (1983) believes both processes can be active during lodgement till formation. On the microscopic level Sittler and Chapman (1955) observed veining and foliation in thin sections made from a diamicton interpreted as a lodgement till. They attribute these features to the impacting and shearing which occurs during the lodgement process.

MELTOUT TILLS

Characteristics of meltout tills from both theoretical and field studies are tabulated in Table 3.2.

Meltout tills, first conceptualized by Goodchild in 1893, (*in* Haldorsen and Shaw, 1982), form when the upper and lower surfaces of stagnant buried ice masses release their entrained debris by slow *in situ* melting under confining overburden conditions which inhibit the deformation and movement of the deposit, preserving the englacial clast fabric and some of the englacial features (Boulton, 1972; Lawson, 1979; Shaw, 1982). Elson

Table 3.2 CHARACTERISTICS OF MELT-OUT TILLS

AUTHOR	CHARACTERISTICS
Elson 1961	-deformed precompressed till sheets -thin silt/clay coatings around clasts -striated boulder pavements -irregular sand lenses at the base -preferred clast fabric parallel or perpendicular to ice flow direction
Dreimanis 1976	-less compact than lodgement tills -laminae of silt or sand from melting of debris-poor ice layers -local lithologies at base distant at top -silt and clay coatings around clasts -fabric parallel or perpendicular to flow -a-b axial plane horizontal
Boulton 1976	-always overlain by diamictons of another facies -grain size uniform -no banding but faint stratification may be present -no folding -rare joints -thin, unlikely to exceed 2 meters -fabrics parallel or perpendicular to ice flow direction, a-b horizontal, consistent in site assemblage of fabrics
Lawson 1979	-tabular geometry, meters in thickness kilo meters in breadth -lack of distinct, continuous internal contacts -massive appearance with discontinuous layers, lenses, and pods of texturally distinct sediment -sets of strata from debris rich ice may give rise to diffuse laminations with poorly defined boundaries -unconformable, abrupt contacts between sediments with different sedimentological origins -bands of cohesive sediments may be preserved and may appear to drape clasts due to differential meltout -strongly developed unimodal clasts fabrics which form a consistent assemblage parallel to ice flow, a-b axial plane horizontal
Shaw 1977a,b	-subhorizontal partings representing foliation which has melted out -sublimation meltout -crude irregular bedding -augen and truncated structures preserved by sublimation -internal folded foliation possible -massive lower layer with a foliated upper layer
Shaw 1979, 1983	-Sveg Tills -draped clasts due to differential subsidence upon meltout of enclosing ice -sorted layers from the meltout of debris poor ice layers and water flowing along low debris content layers

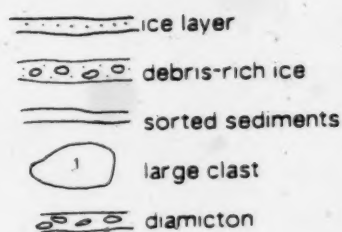
Table 3.2 continued

AUTHOR	CHARACTERISTICS
Shaw 1982, 1983	-crosscutting of sorted layers by clasts -strong, clast fabrics parallel to ice flow direction
	-incorporated clasts of sub-till material not streaked out -in situ stratified deposits with sharp upper contacts and conformable lower ones -convex upward lenses of stratified deposits -scours beneath boulders projecting downwards from the diamicton into the stratified sediments -till fabrics parallel to flow and consistent over a large area
Haldorsen and Shaw 1982	-'configuration of till with a recognizable textural or lithologic property closely related to the configuration of englacial debris with the same property' -presence of unlithified sorted and stratified sediment within or interstratified with the tills -statistically preferred pebble orientation -all three of these properties must be present before a meltout till genesis can be inferred

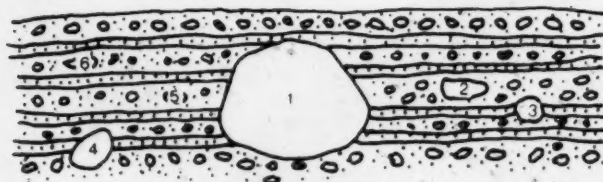
(1961) theorized that a volume loss of 70% to 90% accompanying meltout would cause deformation of thin sheets of precompressed debris enclosed within the ice but the englacial clast fabric would be preserved. Thin silt and clay coatings around clasts as well as sand or pebble lags at the base of the deposit may also be present (Elson, 1961; Boulton, 1976a,b). Pebble clast fabrics are usually described as well-developed and parallel to flow (Boulton 1976a,b; Shaw 1976; Kruger 1979; Dreimanis 1976). Boulton (1972), stated that meltout tills could only be distinguished from flow deposits by their well-developed fabric.

Meltout tills are usually thought to be massive, but Shaw (1977a,b) describes a multiple meltout till unit with a massive lower member and a stratified upper member. Shaw (1977a,b) postulated that a cold-based ice sheet over-riding its frontal apron would form a basal poorly-attenuated debris zone in which the debris has been transported only a short distance, and an upper, highly-attenuated zone composed of debris which has been transported a great distance. Upon stagnation the debris in these zones is released from the ice by meltout forming a lower massive facies with a high percentage of local clasts and an upper stratified unit with a predominance of exotic clasts. Meltout processes preserve some of the englacial features of both in the stratified unit, sand laminae are formed by deposition of sorted sediments along foliation planes within the ice. Meltout of the foliation planes imparts the stratification to the unit. Clasts which cross-cut sand laminae represent clasts which originally cross-cut foliation planes within the ice. Shaw (1979) interpreted the Sveg till of Sweden in much the same manner but the higher volume of meltwater present in the less arid environment of Sweden when compared to the Antarctic, resulted in the deposition of thicker laminae of sorted sands and silts along foliation planes and within cavities arising in debris poor ice layers. Complete melting of the ice produced a stratified deposit in which clasts which had originally cross-cut foliations in the ice truncate the sand laminae formed along these foliations (Fig 3.1). Clasts, which were larger than the debris layers in which they were enclosed, upon meltout project above the surface of the diamicton and are draped by sand laminae due to differential subsidence which occurs during complete meltout (Fig 3.1). The diamictons in the stratified layers possess well-developed, parallel to flow, unimodal clast fabrics.

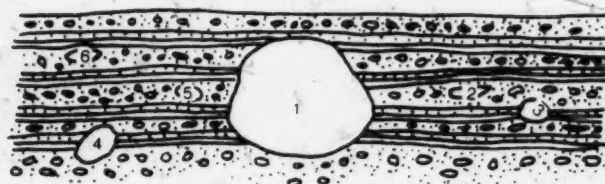
Figure 3.1 Production of sedimentary features during the formation of a meltout till. Draping of large clasts is caused by differential subsidence. Clasts (3, 4) which originally crosscut foliations cause abrupt terminations of laminae of well-sorted sediments upon meltout. Clasts totally enclosed in diamicton do not cause any deformation in the diamicton or layers of stratified sediments. Note the lack of deformation of laminae and diamictons below the large clasts and the downwarping of laminae at the intersection points with the large clasts (after Shaw, 1979).



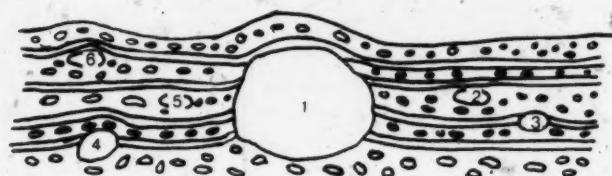
Time 1



Time 2



Time 3



Shaw (1982, 1983), assigns a meltout origin to the diamictons in the Villeneuve, Alberta, area on the basis of their well-developed, consistent clast fabric, the inter-relationships between the sand lenses and the enclosing diamicton, and the presence of boulder scours within the diamictons and the stratified sediments. Haldorsen and Shaw (1982), used an assemblage of three properties to separate meltout tills from tills of other origins in Norwegian glacigenic deposits. These properties were: (1) the presence of a statistically preferred pebble orientation, (2) the presence of unlithified sorted and stratified sediment within or interbedded with diamicton, and (3) "the presence of a recognizable textural or lithological property closely related to the configuration of englacial debris (such as discontinuous pods and lenses of texturally distinct material)".

All the foregoing criteria for the recognition of meltout tills were developed from interpretations of the formation of Pleistocene glacigenic diamicton deposits. Only Lawson's (1979) research, on the processes of sedimentation active at the present day terminus of the Matanuska Glacier, develops criteria for the identification of meltout tills from detailed field descriptions of the transition from stratified debris-rich ice to final meltout till deposits. Preservation of englacial features within the meltout till is controlled by the amount and distribution of the debris in the ice (Lawson, 1979, 1981). Lawson (1979) observed that the debris contained within the ice was distributed in bands and that the sediment concentration within individual bands, was highly irregular as each band was composed of irregular aggregates, isolated grains, or rapidly varying lenses, layers, and discontinuous pods of debris randomly dispersed through the ice. A summary of investigations (Table 3.3) on the distribution and concentration of debris within glaciers and ice sheets indicates that the irregular distribution of debris as seen by Lawson (1979) is not unusual but occurs in both temperate and arid environments; in glaciers, ice caps, and ice sheets. This table also shows that the concentration of the debris within the ice is usually less than 4% by volume.

Figures 3.2a, b, and c schematically show the transition from debris stratified ice to final deposit for three meltout tills (Lawson, 1979). Solid layers of cohesive sediments overlying bands of low debris content ice were deformed or disrupted upon meltout as had been hypothesized by Elson (1961). Bands with high debris content differing in color or texture from the surrounding debris would be identifiable in the subsequent deposit but

Table 3.3 Distribution of Debris in Ice Sheets, Ice Caps, Ice Bergs, and Valley Glaciers

Author	Ice Sheet	Ice Type	Debris
Anderson et al 1980 Koerner and Fisher, 1979	Antarctic Devon Island Ice Cap	Calved Icebergs Cold-based	Foliated bands, 4.8-77.8% by weight < .001% by volume, microparticles
Herron and Langway, 1979 Boulton, 1975	Greenland Ice Sheet Swiss Alps, Norway Iceland	cold-based Temperate Glaciers	debris zone 15.7m thick, maximum debris 9% by weight, 4% by volume debris concentration 5 to 40-50% distributed in a thin zone 10-20 cm thick exceptionally 1m thick
Boulton, 1972	Barnes Ice Cap	cold-based	debris zone 30.5 to 61 m thick, average debris concentration 5% by volume
Andrews 1972 Holdsworth, 1973	Devon Island Barnes Ice Cap	Ice-cored moraine Cold-based	debris concentration 5% by volume folded dirt bands 1m to 2m thick dirt bands debris concentration 8% $\pm$ 3% by volume, clean ice .08% debris by volume
Goldthwait, 1951	Barnes Ice Cap	Cold-based	debris zone 30.5m to 61 m thick debris bands, .01 m to 1 m thick, lateral continuity normally 10 to 100 ft, exceptional 1,000's of feet, separated by clean ice 5 to 15 cm thick, isolated rocks.
Ward, 1952	Barnes Ice Cap	Cold-based	debris bands < 1cm to several cm thick large isolated clasts.
Gow, Epstein, and Sheehy, 1979	Antarctica	Cold-based	debris zone 4.83 meters, irregular horizontal bands, layers of clay, sand pebbles; debris concentration of bands by weight 12%, 15.7%, 15.3%, by volume < 7%.
Swinow, 1962	Greenland Ice Cap	Cold-based	debris zone 60-90 m thick, bands are distorted irregular masses of sediment, some bands are vertical, larger debris bands are composed of smaller 2-12mm layers, bands are laterally variable in thickness and texture, debris concentration 1-40% by volume.
Hamilton and Hays, 1961	Taylor Glacier, Antarctica	Cold-based	debris zone 10m thick, bands folded and sheared, continuous for 10's of meters, range from < 2cm to 20 cm, a nearly horizontal foliation is sometimes present.

Table 3.3 Distribution of Debris in Ice Sheets, Ice Caps, Ice Bergs, and Valley Glaciers

Author	Ice Sheet	Ice Type	Debris
Boulton, 1967	Vestspitsbergen Sorbreen Glacier	Temperate Ice	debris bands up to 1 m thick, bands vary irregularly in thickness laterally, can be contorted, several textural changes observed in a single band debris content usually <7% by volume, rarely 15% by volume
Boulton, 1968	Dunereen Glacier Vestspitsbergen	Temperate Ice	debris bands 5-5m thick separated by clean ice bands 0.04m to 5m thick, isolated clasts distributed through the ice, debris bands can be dipping, folded or replicated by thrusting
Hooke, 1970	Antarctica	Cold-based	debris concentration 30-80% by volume four facies (1) solid interstitial ice only >10% debris by volume (2) banded dirt bands 1-5mm thick which separate and rejoin are not solid but consist of dispersed sand and silt grains, rare pebbles and cobbles crosscut several debris bands, debris concentration 1-2-4% by volume (3) sandy amber, a few sand sized grains dispersed in the ice, debris concentration 2% by volume (4) amber no visible grains, color due to dispersed particles, debris concentration 0.04% debris in several facies (1) bands irregular lateral extents, variable thicknesses for a single debris band, rapid variations in texture, continuous for 10's of meters, debris concentration 0.1-74% by volume, (2) discontinuous layers, 1-2m thick, 10-20m in length, contain irregular aggregates of debris, same range in debris volume, (3) clean ice layers, occur between debris bands are irregular in thickness, the different facies are randomly distributed through the debris zone, folding and thrust stacking are common.
Lawson, 1979	Matanuska Glacier Alaska	Temperate Ice	

Figure 3.2 Formation of surface and basal melt-out tills observed at the terminus of the Matanuska Glacier.

3.2A. Formation of a massive basal melt-out till.

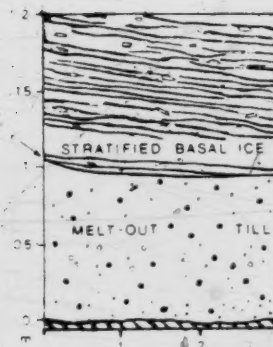
3.2B. Formation of a stratified basal melt-out till.

3.2C. Formation of a massive surface melt-out till.

(After Lawson, 1979).

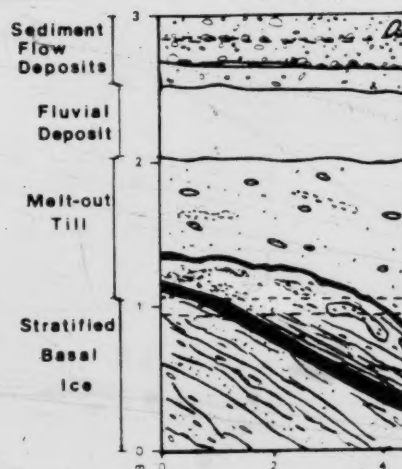
A

Formation of massive, basal, melt-out till from melt-out of stratified low-debris content ice.



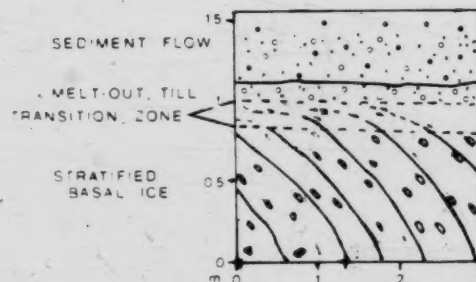
B

Melting of basal stratified ice with high debris contents ($> 50\%$) produces a surface melt-out till. Melt-out causes the high debris content layers to decrease in dip and differential subsidence causes folding in these layers. The sharp contacts between stratified sediment and ice become diffuse upon melt-out.



C

Formation of a surface melt-out till by melting of stratified ice under a sediment flow cover. There is a total loss of stratification within the resulting deposit.



their contacts would be diffuse and indistinct due to the particle readjustments which occur upon meltout. Meltout of multiple debris bands with high debris contents (35-50 % debris by volume) in a few instances formed deposits with a faint stratification. Meltout of low debris content layers (<4% debris by volume) produced a massive deposit. Sand lenses and pods of coarser material which possessed sharp boundaries when enclosed within the ice, upon meltout, possessed vague diffuse contacts due to particle readjustments which occur during the meltout process. All the meltout tills observed by Lawson possessed fabrics which were strong, unimodal, and formed a set of orientations with a consistent regional pattern which paralleled the direction of ice flow. From his research Lawson (1979) developed four criteria for the recognition of meltout tills:

1. strongly developed unimodal pebble fabric forming a consistent regional pattern,
2. tabular geometry varying from meters in thickness to kilometers in breadth,
3. lack of distinct, continuous, internal contacts,
4. generally massive appearance within which discontinuous layers, lenses, and pods of texturally distinct material may infrequently occur.

The four main criteria used by Lawson (1979) to identify meltout tills are in agreement with most of the features theorized to occur in meltout tills (Table 3.2), such as the massive appearance (Boulton, 1972, 1976; Shaw, 1982; Dreimanis, 1976), the strong unimodal fabrics (Elson, 1961; Boulton, 1972, 1976; Shaw, 1977 a,b; 1979, 1982, 1983; Dreimanis, 1976), the presence of thin deformed diamictons which formed layers and lenses of texturally distinct material (Elson, 1960), and the tabular deposit geometry (Boulton, 1976; Lawson, 1979).

Features ascribed to meltout from interpretation of Pleistocene deposits but not observed by Lawson (1979, 1981), are the silt and clay coatings around clasts as hypothesized by Elson (1961). The production of sand and silt laminae formed by the meltout of debris poor ice layers hypothesized by Dreimanis (1976) and critical to the models developed by Shaw (1977a, b, 1979, 1983) were not observed by Lawson (1979). He observed that the meltout of a debris-poor ice layer produced a massive deposit.

D. DEBRIS FLOW SEDIMENTATION AND RELATED DEPOSITS IN THE GLACIAL ENVIRONMENT

Debris flows are common in both glacial and nonglacial environments. Prior to the late 1960's investigation on debris flows was primarily concerned with describing their morphology, velocity, and distance of movement (Blackweller, 1928; Frixell and Horberg, 1948; Crandell, 1957). One exception to this, was Bagnold's (1954, 1956), research on slurries containing spheres from which the concept of dispersive pressure was developed to explain the migration of the spheres to the outer margins of the slurries during movement. Johnson (1969, 1970), using field observations and mathematical modelling developed a model of debris flow mechanics in which a lower zone of shear was overlain by an undeforming rafted plug. In the shear zone, dispersive pressure causes the clasts to migrate to the zone of least shear (the largest clasts moving to the top of the shear zone) forming inverse grading in the shear zone and initiating stratification in the flow. As the velocity of the flow increases, the size of the rafted plug decreases until a velocity is attained where the entire flow is in shear. At this point the flow is moving downslope by laminar flow. Dispersive pressure in the flow causes clast segregation with the largest clasts moving to the zone of least shear at the top of the flow. If the flow comes to rest at this time the shear stratification may be preserved, producing a deposit in which inverse grading and a subhorizontal a-b axial clast fabric imbrication (due to the laminar nature of the flow) is present (Fisher, 1971; Enos, 1975; Naylor, 1980). If the velocity increases past the point where the entire flow is in shear, the flow passes from the laminar to the turbulent flow regime. The flow is unable to maintain the clasts in suspension and they rapidly settle through the flow to form a lag deposit at the base of the channel (Pierson, 1980, 1981). In this position the clasts may move by traction as bedload or they may be remobilized by later slower moving flows (Pierson, 1980, 1981). A single sediment flow may undergo several transformations from laminar to turbulent flow, each of which will affect the texture and sedimentary features of the deposit (Fisher, 1983). The sedimentary features of debris flows are thus dependent upon their flow histories (Fisher, 1983).

Flow histories are controlled by the properties of the flow such as its velocity, water content, and its viscosity. These are interdependent factors which affect the

sedimentary features of the deposit. Viscous flows have low water contents, move slowly, and have irregular clast distributions with many of the clasts possessing vertically-oriented a-axes (Boulton, 1970a; Bull, 1977; Lawson, 1979; Pierson, 1980). The fabric of these flows is poorly developed (Boulton, 1970a; Bull 1977; Lawson, 1979). Viscous flows form lobate deposits with distinct noses and sides (Boulton, 1970a; Bull, 1977; Lawson, 1979, 1981). As the viscosity of the flow decreases, the flow velocity, shear, and dispersive pressure increases (Johnson, 1970; Boulton, 1970a; Lawson, 1979). Fluid laminarly flowing debris flows possess subhorizontal to horizontal clast imbrications and well-developed clast fabrics may be present (Bull, 1964, 1977, Lindsay, 1970, Boulton, 1971, Fisher, 1971, Enos, 1977, Lawson, 1979, Lowe, 1979). As the flow becomes more fluid, its lobate shape decreases (Lawson, 1979). Very fluid flows are composed primarily of finer grain sizes and require channellization to be able to move long distances and deposit only in depressions and ponds as sheet-like deposits which may possess well-developed clast fabrics (Lindsay, 1968; Lawson, 1979; Pierson, 1981). The clast size decreases with distance from their point of origin (Bull, 1964; Lawson, 1979). If the zone of shear had not extended through the entire debris flow, this inversely graded stratified zone may be overlain by a massive deposit representing the plug zone in which the fabric is random as in a viscous sediment flow deposit (Naylor, 1980; Johnson, 1970; Enos, 1977). Inverse grading, observed by Fisher (1971) and Enos (1977), is attributed to migration of the clasts through the flow by dispersive pressure. As viscosity continues to decrease and the other factors increase the flow becomes unable to maintain the clasts in suspension and they settle through the flow forming a normally graded deposit (Bull, 1964; Pierson, 1980). This settling out from the flow results in a decreasing grain size with distance of flow (Bull, 1964, 1977). Fluidized pyroclastic flows also show a decrease in grain size with increasing distance of movement from the source (Sparks, 1976; Wilson 1979; Wilson and Walker, 1982). If a single flow undergoes several transformations between laminar and the turbulent flow regimes the resulting deposit is extremely complex and highly modified from the material at the source (Fisher, 1983).

Other features of debris flows are mud clasts, armoured mud clasts, and dewatering structures (Bull, 1964; Lawson, 1979; Fritz and Harrison, 1982; Harrison and

Fritz; 1982).

SEDIMENTARY ASSEMBLAGES AT THE STAGNANT TERMINUS OF AN ICE SHEET

Table 3.4 is a summary table of the common sedimentary characteristics of the subaerial stagnation environment.

Sedimentary assemblages within the stagnating terminus zone of ice sheets are dominated by debris flow deposits formed by resedimentation of debris released primarily supraglacially from the ablating ice (Boulton, 1967, 1968, 1972; Lawson, 1979, 1981, 1982). The most common deposits in the stagnation zone of an ice sheet are massive diamictos associated with minor amounts of sediments deposited by other sedimentary processes (Boulton, 1967, 1968, 1972; Lawson, 1979). These diamictos are difficult to distinguish from the diamictos deposited in other environments by other processes and, therefore the facies associations within the ablation environment assume major importance (Boulton, 1976; Boulton and Paul, 1979; Eyles, 1979). Lawson (1979) noted that common sediments associated with debris flow deposits are massive irregular silt caps formed by meltwater washing and silt deposition in short-lived ponds on top of and adjacent to sediment flow deposits. Single-layer-thick gravel lags representing horizons of subaerial erosion, dewatering structures, dessication cracks, load structures, and intact blocks of source material within the sediment flow were also observed (Lawson, 1979).

The sedimentary assemblages of this environment exhibit rapid vertical and lateral changes due to the constant random shifting of the depositional loci and processes. This juxtaposition of processes is characteristic of the glacial stagnation environment. Landform and facies assemblages which describe variations in the assemblages according to which process is most active in the environment are given by Boulton and Paul (1976) and Eyles (1979).

Sediment flows are not the only depositing agencies in the stagnation zones of ice sheets. Deposition within an ice sheet stagnation zone is characterized by numerous processes which actively rework the deposits. The sedimentary assemblages show rapid variation both laterally and vertically (Hartshorn, 1958; Clayton, 1964; Boulton, 1967, 1968, 1969, 1970; Boulton and Paul, 1976; Boulton and Eyles, 1979; Lawson,

Table 3.4 CHARACTERISTICS OF THE SUBAERIAL STAGNATION ENVIRONMENT

AUTHOR	CHARACTERISTICS
Boulton 1971	-greatest thickness in hollows -interbedded and interdigitating with stratified sediments -desiccation causes overconsolidation -fabric highly variable, strong slope fabric due to creep, viscous sediment flows have many vertical clasts and random clast orientations, less viscous flows have parallel to flow fabrics in the body and perpendicular at the margins, fabrics do not form a consistent assemblage.
Boulton 1968	-water sorting on the top surface gives stratification of limited extent -flow noses -pseudo-stratification produced by streaking during flow -fabric variable spatially if controlled by topography can get consistent downslope flows giving consistent fabrics if topography exerts no control no pattern to flow
Boulton 1976	-topmost in the sequence of tills -occurs in contact with outwash sediments -sediment lenses of all sizes occur in the till -wide variation in grain size -local enrichment in fines due to subaerial washing -sedimentary banding due to water washing the surface -shear banding due to streaking out during flow -flow noses and folding due to flow -high angle faulting where deposited over ice -irregular thicknesses -vertical desiccation joints with a polygonal pattern
Dreimanis 1976	-loose noncompact -coarsened due to loss of fines during washing -texturally variable -interbedded with stratified drift -local fabrics, no consistent assemblage
Marcussen 1973	-alternation of till and stratified sediments -conformable layering between till and sediments -wide textural range -individual layers few 10's of meters -boulder lags -thin uniform layers deposited by less viscous flows, irregular layers deposited by viscous flows -clasts parallel or sub-parallel to bedding -tills are irregularly shaped
Marcussen 1975	-loose and incoherent -associated with sand, gravel, and clay deposits -irregular topography -inconsistent fabrics

Table 3.4 continued

AUTHOR	CHARACTERISTICS
Lawson 1979	-rapid lateral and vertical textural variations -rapid shifts in facies -individual units of varied geometry, orientation, and dimensions -laterally discontinuous units (10 s of meters) -internal irregularly shaped surface contacts with caliche coatings -lines of gravel sized clasts one clast thick with sub-parallel alignments, lag concentrates, and cut and fill structures marking zones of subaerial exposure -individual fabrics weakly developed, bi- and multi-modal, rapidly varying, and forming an inconsistent set of fabrics -Individual flows: massive to graded appearance, intraformational blocks may be present, tractional gravel bases present in more fluid flows, variable surface features with a meltwater facies cap, generally distinct, non-erosional upper and lower contacts, features of flows dependent on their water content viscous flows have numerous vertically oriented clasts, more fluid flows have more horizontal and sub-horizontal clasts

1979). Sheetwash, rillwash, streams, and rivers combine to wash and sort the exposed surfaces to varying degrees. The fines which are removed by the erosional agencies are deposited in hollows and lakes between hillocks and mounds or totally removed from the area. Sediment flows of all types rearrange the sediments, diverting streams and infilling ponds and hollows.

SUBAQUATIC GLACIGENIC SEDIMENTATION PROCESSES AND THEIR DEPOSITS

Table 3.5 is a summary of the sedimentary features of subaqueous diamictons.

Subaquatic glacigenic sedimentation occurs in the glaciolacustrine and glaciomarine environments depositing a variety of sediments ranging from waterlain diamictons, ice-rafted, and suspension deposits to turbidity and bottom current deposits.

Early models of ice shelf sedimentation (Carey and Ahmad, 1960) have been shown to be largely incorrect and have been superseded by newer models (Drewery and Cooper, 1981; Orheim and Elverhoi, 1981). These models and studies on the bottom sediments of the Antarctic seas (Kurtz and Anderson, 1979; Anderson *et al.*, 1980a,b; Wright and Anderson, 1982; Domack, 1982), are applicable to the interpretation of glaciolacustrine deposits due to the similarities that exist between the two environments.

Studies of sedimentation from floating ice shelves indicate that most of the basal debris is released at or near the grounding line (Drewery and Cooper, 1981; Orheim and Elverhoi, 1981). Detailed studies of the bottom sediments of the Antarctic continental rise have shown that both massive and stratified diamictons are present (Kurtz and Anderson, 1979; Anderson *et al.*, 1980a,b; Wright and Anderson, 1982; Domack, 1982). Two types of stratified diamicton are present. The first is bimodal and texturally heterogenous with stratification varying from 1mm to 5 cm in thickness. Single strata possess diffuse and discontinuous upper and lower contacts. Clast fabrics are poorly developed. Some of the clasts have sub-horizontal imbrications. These are interpreted to be deposited by a combination of ice-rafting, which introduces the coarser particles and clasts and pelagic sedimentation, which supplies the more abundant clay and silt fraction, and winnowing by bottom currents which creates areas depleted or enriched in fines, forming the laminae between the diamicton layers. Irregularities in the strength of the bottom currents and in the distribution of pelagic sediments over short distances causes the formation of the

Table 3.5 CHARACTERISTICS OF WATERLAIN GLACIGENIC DIAMICTONS

AUTHOR	CHARACTERISTICS
Driemanis 1982	-Catfish Creek, Ontario -Evenson et al 1979 -intercalated sand and silt laminae -Gibbard 1979 -and diamictons -laminae of stratified sediments a few mm to 50 cm, gradational contacts beneath thinner ones, erosive contacts beneath thicker laminae. -laminated silt and clay intraclasts -diamictons are massive -isolated clasts and nests of clasts interpreted as dropstones, with vertical and horizontal a-b axial planes -flow noses -recumbent folds due to slumping -sole marks beneath the diamictons
Kurtz and Anderson 1979	-Ross and Weddel Seas, Antarctica -Anderson et al 1980 -interbedded stratified pebbly -Domack 1980 -mud and massive muds -stratification due to silt and sand laminae -stratified muds bimodal and texturally inhomogeneous -gradational contacts which are indistinct -stratified muds have deep water fauna -stratified muds interpreted as a mixture of pelagic sedimentation with clasts due to iceberg rafting -massive muds texturally homogeneous and polymodal -contacts sharp and distinct -interpreted as subaqueous debris flow deposits
Huddart 1983	-England -deformed clasts of laminated silt and clay -oval clasts of green till in red silt matrix -intraclasts composed of sand sized particles enclosed in a silt matrix -rare pebble and gravel bands -silt laminae deposited by density underflows -diamictons deposited by sediment flows -cut and fill structures present -occur as isolated flat-topped hills -well-developed macro- and microfabrics due to flow down a consistent slope
Powell 1976	-Glacier Bay Alaska -glaciomarine deposits in front of rarely calving glaciers -posses mud and sand muds approx. 1 cm thick sands 1-2 mm thick, isolated pebbles, sequences of laminated mud further seaward and in areas of the ice margin where there is no influence from inflowing streams. -glaciomarine deposits in front of actively calving glaciers, sandy gravel or pebbly diamicton at calving margin, calving keeps fines in suspension, redeposition

Table 3.5 continued

AUTHOR	-CHARACTERISTICS-
	by sediment flows initiated by calving.
Schmoll 1961	-Coppermine River Basin, Alaska - Ferrians 1963 -interbedded diamictons and sorted - Nicols 1963 - sediments -diamictons <2.5cm to approx. 40 cm. -diamictons are stratified with thin laminae of sand, silt, and gravel -diamictons alter with bedded lacustrine silts -dropstones in the bedded silts -dropstones have a-b axial planes horizontal and a weak preferred alignment to these planes -also pods of unsorted diamicton in the silt beds -slumping and intraformational folding present
May 1977	-Glacial Lake sediments in Edmonton and Peace River -diamictons containing rounded or elongate intraclasts of silt and clay -diamictons massive or crudely stratified -the diamictons were interbedded with normal lacustrine sediments -flow and deformation structures common -random clast fabric unaligned with the ice flow direction
Link and Gostin 1981	-PreCambrian Staurian Tillite, Australia -interbedding of diamictons and turbidity current deposits -diamictons have deformed soft sediment clasts -till pellets with diffuse boundaries present in the diamictons -intraformational folding present -isolated clasts and pods of diamicton in the turbidite deposits -cobbles and boulders pierce the bedding of the turbidite deposits
Visser 1983	-Upper Carboniferous Dwyka Tillite, South Africa -interbedded diamictites, sandstones, siltstones and rhythmic shales -single dropstones and nests, isolated diamicton pods -dropstones pierce bedding and truncate thin sediment flows -diamictite massive, stratified or faintly stratified -diamictite contains deformed mud clasts and diamicton pellets -clasts project above the surface of the diamictons into the bedded sediments -rhythmic shales few mm to 25 cm thick, contain ripples, show evidence of soft sediment deformation -deformation structures in the diamictites due to movement as a sediment gravity flow

diffuse irregular contacts between layers. The second stratified diamicton type is polymodal, texturally homogeneous, and possesses sharp, continuous upper and lower contacts between strata. These are interpreted to represent subaquatic debris flow deposits. Massive diamictons on the Antarctic continental rise are overconsolidated, thick, and areally correspond to former locations of ice sheets and have been interpreted as basal tills (Anderson *et al.* 1980a,b; Wright and Anderson, 1982; Domack, 1982).

Stratified diamictons interpreted as forming in a glaciolacustrine setting have been described by Evenson *et al.*, (1977); May (1977); Gibbard (1980); Link and Gostin (1981); Visser (1983); and Huddart (1983). The most commonly applied models for deposition of glaciolacustrine diamictons are the subaquatic debris flow model of Evenson *et al.* (1977); and Gibbard's (1980) model of "rainout" from beneath the margin of a slightly floating ice sheet (Gibbard, 1980). Evenson *et al.*'s model is based on the coalescence of subaquatic debris flows which originate from the terminus of an ice sheet grounded in a lake. The deposits consist of diamictons interbedded with thin laminae of sorted sands and silts. The diamictons are unsorted, ungraded, texturally homogeneous with a random clast-fabric, and flow and load-structures associated with them. Laminae of silt and sand, interpreted as deposits of turbidity and bottom currents, are loaded, deformed, and disrupted by the overriding debris flow. Gibbard (1980) interpreting the same sediments hypothesized a "rain-out" deposition of debris from a slightly floating ice sheet to form the diamictons, and winnowing by bottom currents to form the laminae of sorted sediments. The apparent contradiction of the two models was clarified by Dreimanis (1982), who applied Evenson *et al.*'s (1977) model for the lower parts of the sections (exposed when this model was developed) and Gibbard's (1980) model for the upper parts of the sections (which were exposed at the time of Gibbard's fieldwork).

Calving mechanisms and the deposits associated with calving ice fronts and icebergs have been described by Ovenshine (1970); Holdsworth, 1973a,b; Barnett and Holdsworth (1974); Powell (1979, 1981); and Sugden and John, (1976). Ice sheets which ground in shallow lakes usually undergo brash ice calving producing small icebergs which release the bulk of their entrained-debris at the grounding line (Sugden and John, 1976). Grounded ice may also have parts of its margin undermelted, forming large overhangs beneath which the debris released by undermelting accumulates to form subaquatic debris

banks (Holdsworth, 1973a,b Barnett and Holdsworth, 1974). These are also called rib moraines, de Geer moraines, or cross-valley moraines and are interpreted as representing the terminal portions of ice sheets which had grounded in lakes. Floating ice sheets and ice margins on the other hand, form larger more tabular icebergs which drift throughout the lake releasing their debris over a larger area. Large icebergs can scour and gouge the sediments at the bottom of the lake (Clayton *et al.*, 1969 while *in situ* melting of grounded icebergs releases their debris forming large irregular bergmounds (Fecht and Talman, 1978).

Powell (1979, 1981) describes the deposits associated with frequently and infrequently calving tidewater glaciers. The dominant sediments in front of rarely calving tidewater glaciers are interbedded muds and sands deposited in subaqueous deltas. Frequently calving tidewater glaciers have coarse sandy gravels or pebbly diamictons associated with them as the calving maintained the fine grained material in suspension to be removed by current action.

ICEBERG SEDIMENTATION

Ovenshine (1970) investigated the processes of sedimentation by icebergs in Glacier Bay, Alaska. Ablation of icebergs as they float allows the accumulation of large volumes of debris composed of diamicton pellets, pebbles, and fine grained sediments, on their upper surfaces, which is deposited when the iceberg capsizes. This emplaces clusters of clasts, irregular blocks of diamicton, and diamicton pellets into the bottom sediments. These clasts (dropstones) distort the layers below them by the force of their impact, often forming a mirror image of the clast shape (Hardy and Legget, 1960). The dropstones can pierce bedding (Link and Gostin, 1981; Huddart, 1983; Visser, 1983) and are, in turn, draped by sediments introduced from suspension, bottom currents, turbidity currents, or sediment flows (Evenson *et al.*, 1977, Link and Gostin, 1981, Huddart, 1983).

Although Gibbard (1980) writes of a "typical dropstone orientation", the orientation of dropstones is problematical. Domack (1982), Griggs and Kulm (1975), and Dalland (1976) state that dropstones have a vertical orientation. Evenson *et al.* (1977) state that dropstones have a horizontal a-axis orientation. Gibbard (1980) states that dropstones have a vertical a-axis orientation with sub-horizontal orientations caused by tipping of the

clast into a more stable position after impact or clast reorientation after deposition by slumping and flowage. Schmoll (1961) concluded from the analysis of 5 sets of 100 pebbles in 5 non-coeval beds of laminated lake sediments that dropstones had a horizontal to sub-horizontal a-b axial plane orientation and a weakly-developed a-axis orientation. He hypothesized that the alignment of the a-axis was caused by lake currents as the clast descended through the water column. Horizontal to sub-horizontal a-b axial plane orientations are not diagnostic of dropstones as horizontal to sub-horizontal a-b axial plane orientations have also been observed among clasts deposited in meltout tills and for clasts deposited in laminarly flowing sediment flows (Boulton, 1970a; Lindsay, 1970; Fisher, 1971; Bull, 1977; Lawson, 1979).

SOFT SEDIMENT CLASTS

A ubiquitous feature of waterlain diamictons are intraclasts or soft sediment clasts. Table 3.5 lists the studies in which waterlain diamictons containing intraclasts have been described. May (1977) states that the soft sediment clasts are a diagnostic feature of waterlain diamictons. Till pellets, composed of mixtures of rock flour and angular silt and sand grains, are demonstrated by Ovenshine (1970), to "uniquely identify the existence of glacier ice near the environment of deposition" as no other form of ice rafting (organic or shore ice rafting) are associated with diamicton pellets. These diamicton pellets have been described in waterlain diamictites by Schenk (1965) and Link and Gostin (1981), who also noted the diffuse vague contacts that occur between these intraclasts and the surrounding diamicton matrix. Shaw (1982) uses the presence of blocky clay clasts to differentiate between waterlain diamictons and meltout tills. aquatic, glaciogenic diamictons.

GLACIOLACUSTRINE SEDIMENTATION BY DENSITY CURRENTS

Turbidite deposition in ice proximal glacial lakes was first discussed by DeGeer (1898). Many subsequent studies (Banerjee, 1973; Ashley, 1975; Harrison, 1974; Kuenen, 1951) have described the deposits of lacustrine and glaciolacustrine turbidites. Ashley (1973) describes the differences between proximal and distal rhythmites (Fig. 3.3). The silt component of proximal rhythmites which are composed of a lower graded silt component and clay upper components, is thicker than the clay component. Proximal rhythmites may

also be composed of sands which have ripple drift cross-laminations of several types (Jopling and Walker, 1966). Distal rhythmites are predominantly graded silts with the clay components of the rhythmite much thicker than the silt component (Ashley, 1976). Banerjee (1973) describes diamictic varves in which clasts of diamicton are suspended within the silt layers. Harrison (1975) describes beds composed of graded silt laminae with sharp erosional bases and beds of ripple drift cross-lamination. Both are interpreted as deposits of turbidity currents. Ripple drift cross-beds indicate tractional deposition and high rates of suspended sediment fall-out (Harrison, 1975) and are associated with a proximal delta location (Ashley, 1975).

IV. DESCRIPTION OF THE FACIES

A. THE FACIES APPROACH

A facies approach was used in the description of the sediments in the field.

"The term facies has been used in many different senses: (1) in the strictly observational sense of a rock product eg. 'sandstone facies'; (2) in a genetic sense for the products of a process eg. 'turbidite facies', (3) in an environmental sense for the environment in which a rock or suite of rocks is thought to have formed; and (4) as a tectofacies, eg. 'post-orogenic facies'...."

Reading (1978). Facies in this thesis is used in the sense of a body of sediment with specified characteristics and therefore can also be called lithofacies. Each facies was defined on the basis of its composition, texture, colour, and sedimentary structures. Detailed investigation of the sedimentary properties of the diamicton facies was undertaken to identify their depositional processes and environments. The characteristics of the more readily identifiable facies (eg. Facies 13, the rhythmite facies), were less intensively studied. Full section descriptions and section diagrams are located in Appendix 1. The location of the plates and various sample types locations are given in Figs A1.1 to A1.7 in Appendix 1. In the following section field descriptions are placed under the heading of Field Descriptions. Characteristics determined by laboratory analysis are presented under the heading Laboratory Data. Emphasis was placed on determining the genesis of the diamicton facies since the genetic identification of glacial diamictons is difficult due to the similarities between glaciogenic diamictons of different origins. The lack of detailed sedimentological descriptions of diamictons regardless of their genesis also hampers the identification of the origin of diamicton deposits. Glaciofluvial and glaciotectonic facies were not described in detail as their general depositional environments and processes which are easily identified were of sufficient depth for the purposes of this thesis and detailed investigation was unnecessary.

Thirteen facies were recognized in the study area. Of these 13 facies, five were found in several sections in a repetitive sequence while the others were restricted to one or two sections. To enable the reader to form a clearer image of the associations between facies and their aerial distribution a table (Table 4.1) listing the sections and the facies they

Table 4.1 SECTIONS STUDIED AND THE FACIES WHICH THEY CONTAIN

Section	Facies	Present				
Highway 13 Roadcuts	1					
Delta Pit Site	4	5				
Ridge Section 1	3	5				
Ridge Section 2	3	5				
Hummocky Sand Pit	2	5				
Riverbend 1	6	8	9	10		
Riverbend 2	7	8	9	10	13	
Main Section	7	8	9	10	13	
Kettle Section	7	9	7			
New Pit South	6	8	9	10	13	
New Pit West	6	8	9	10	13	
New Pit North	6	8	9	10	11	
Old Pit	(2)	6	8	9	10	13
Far Bridge Section	7	8	9?	10	7	
West Pit Section	12	13				

contain and a map (Fig 1.2) showing the location of the sections in the study area are provided. A detailed discussion of the facies associations, the common sequences of facies, and their distribution through the study area will be undertaken in Chapter 5.

B. DESCRIPTIONS OF FACIES 1 THROUGH 13

FACIES 1, DEFORMED AND DISPLACED BEDROCK FACIES

FIELD DESCRIPTION

This facies is found to the south and southwest of Bittern Lake at the northern part of the study area. Folded, faulted, and distorted slabs of local bedrock were observed in numerous roadcuts that transect irregular hillocks 2 to 30 meters in height and ten's to hundred's of meters in length.

INTERPRETATION OF FACIES 1

Moran *et al.* (1980) and Fenton (1983) have described terrain associations in which shallow lakes and depressions, the source areas of the ice-thrusted material are located up-ice of ice-thrusted bedrock hummocks. In the study area immediately north (up-ice) of the hummocks containing the folded and deformed bedrock blocks is Bittern Lake (see map 1.2). The hummocks are largest near the lake and diminish in size in a southerly direction. These features fit the pattern described by Fenton (1983) and support the interpretation that the hummocks were formed by glaciotectionism. There is no evidence of streamlining or erosion by overriding glacial ice indicating that these hummocks must have originated during the late stages of the last glaciation in the area. The hummocks also indicate the approximate location of an ice marginal position as glaciotectionism is believed to occur in the transitional zone between wet-based interiors and cold-based marginal areas of ice sheets (Moran *et al.*, 1980; Fenton, 1983). A further implication of glaciotectionism in this area is that conditions were favorable for entraining large volumes of subglacial material into the ice, from where it can be transported and subsequently released to form thick deposits of glacial sediments.

FACIES 2, SORTED AND BEDDED SANDS AND GRAVELS WITH MINOR DIAMICTON INTERBEDS

FIELD CHARACTERISTICS

This facies (Plates 4.1, 4.2) consists of stratified sands and gravels which contain abundant feldspathic, granitic, and gneissic clasts. Individual beds of sand and gravel are well-sorted and typically contain sub-rounded to rounded clasts. Trough, ripple, and planar crossbeds are present throughout the sections. Well-developed soft sediment deformation is observable in some of the exposures (Plates 4.2). Numerous high angle normal faults were observed throughout the deposits. A single 0.68 m thick, apparently massive diamicton enclosed within the sorted and stratified sediments was observed in one exposure in the Hummocky Sand Pit Site. The diamicton contained discontinuous lenses of sand, tens of cm long and a few cm thick. Faults observed in the enclosing sorted and stratified sediments continued through the diamicton undeflected.

The terrain in the vicinity of the sections was composed of high relief hummocks. Examination of borrow pits in this terrain indicated they were composed predominantly of well-sorted, stratified sands with abundant normal faults.

INTERPRETATION OF FACIES 2

Facies 2 is composed of bedded and sorted sands and gravels with a high proportion of Canadian Shield clasts indicating that it is a glacially-derived deposit and not deposited by the pre-glacial Red Deer River. Sedimentary features such as trough and planar cross-beds indicate that these sands are fluvial deposits. Diamictons enclosed in sorted sediments have often been described from sections in the stagnation zones of stagnating ice sheets (Hartstorn, 1958; Clayton, 1964; Boulton, 1967, 1968, 1972a; Lawson, 1979). Shaw (1972) describes their presence in stratified kame deposits. It is unlikely that the diamicton observed was deposited by a local readvance of the ice due to the conformable contacts with the stratified sediments which surround it. They most likely represent sediment flows from nearby stagnant ice. The sands and gravels indicate a ice contact / ice proximal position such as a sandur or braid plain. The kettles and high-angle normal faults formed when ice blocks enclosed within the stratified sediments melted out.

Plate 4.1 The Hummocky Sand Pit Section (section number 5, Fig. 1.2).

The sand pit in the hummocky terrain massive gray brown unit in the center of the plate is a diamicton containing mudclasts. This diamicton is numbered 1.



Plate 4.2 Close-up of the soft sediment deformation in the Hummocky
Sand Pit Section (knife handle is 9 cm).



FACIES 3, RIDGED STRATIFIED SILTS AND SANDS

FIELD DESCRIPTIONS

This facies appears in two locations. On the east side of the Battle River the sections containing this facies form a ridge-shaped geomorphic feature standing 2 to 8 meters above the general plain level and are conformably draped by Facies 5, the highly altered diamicton. In the Old Pit Section on the west side of the Battle River this facies is overlain by facies 8, 9, 10, and 13. At this locality the ridge-shaped deposit has no surface expression.

This facies consists of planar, ripple, and trough cross-bedded silts, sands and gravels, numerous scours and other erosional surfaces. The sediments are predominantly quartzitic sands with a high percentage of feldspathic, granitic, and other exotic clasts. Facies 3 has gradational contacts with Facies 5 and sharp conformable contacts with Facies 8 which overlie it. The strata in Facies 8 are draped over Facies 3, forming an arch-like structure (Plate 4.3).

INTERPRETATION OF FACIES 3

The sorted and stratified nature of the sediments indicates that they were deposited by flowing water. The erratic clasts, association with glacial diamictons, and its elongate ridge-like form indicate a glacial origin for this facies, mostly likely an esker. The presence of the esker suggests that this region was near the terminus of a stagnating ice sheet as eskers are most commonly associated with stagnant ice settings (Rust and Romanalli, 1975). The lack of deformation and disruption of the esker indicates that the esker has not been overridden by subsequent ice sheets and therefore, must be related to the wasting of the last ice sheet in the area. The arch draping of Facies 3 by Facies 8 in the Old Pit West section could occur if the esker was enclosed in ice which subsequently melted out allowing subsidence of Facies 8 around the esker (Plate 4.3) as has been described in Lake Malaspina (Gustavson, 1975).

FACIES 4, POORLY SORTED STRATIFIED SANDS AND GRAVELS WITH PLANAR FORESET BEDS

Plate 4.3. Picture showing the arch draping of Facies 8 over Facies 3 in the Old Pit Section. Putty knife is 10 cm.



FIELD DESCRIPTION

Facies 4 is found in a site on the north side of the Battle River where its thickness is 22 m. The most noticeable sedimentary feature is the large (10m) planar foreset beds which are composed of gravel to cobble-sized material with silts and sands infilling the interstices between the large clasts. The foreset beds indicate a south to south-easterly flow direction. Many of the cobbles are granites, gneisses, or other Canadian Shield clasts and the sands contain 5 to 10 percent feldspathic grains.

INTERPRETATION OF FACIES 4

The large foresets indicate that this is a delta deposit while the presence of gneisses and granites in Facies 4 indicates that these deposits are glacially-derived sediments. The poorly-sorted nature of the sediments is evidence that they were deposited rapidly by streams which were choked with sediment. This could occur in a delta developed by streams flowing from a nearby ablating ice sheet.

FACIES 5, OXIDIZED, INDURATED, ORANGE-YELLOW DIAMICTON

FIELD CHARACTERISTICS

This diamicton facies varies from 0.75 to 4.0 m in thickness. Rare rounded to sub-rounded clay intraclasts from a few millimeters to approximately two centimeters in diameter were observed within the diamicton but the highly indurated and altered nature of this facies prevents detailed descriptions of its sedimentary features. In the thickest exposure of this facies, the Delta Pit site, sand laminae were seen in the lowest part of the facies. Higher in this section poorly-defined banding, possibly due to minor textural variations, occurs. Facies 5 is the uppermost sedimentary unit in the eastern part of the study area and appears as a blanket deposit which drapes over Facies 2, 3, and 4. The contact between Facies 5 and these underlying facies is gradational.

INTERPRETATION OF FACIES 5

Facies 5 is a highly altered silty diamicton. It directly overlies Facies 2, 3, and 4 with which it has gradational contacts. Facies 5 is thickest above Facies 3 which occurs at the lowest elevation. The high degree of alteration does not permit the identification of

features which could be used to positively identify its origin. The silty nature, low stone count, tabular geometry over a large area, its draping relationships and gradational lower contacts, are consistent with an interpretation that this facies was deposited in a glacial lake. Facies 5 may correspond to the silt till of Warren (1956); which he states appears in some exposures to have been deposited in a lacustrine setting.

FACIES 6, THE UNSTRATIFIED DIAMICTON FACIES

FIELD CHARACTERISTICS GENERAL DESCRIPTION

This facies (Plates 4.4) is 0.76 to 1.2 m in thickness and is composed of massive gray-black diamicton containing 3-5 % predominantly gravel-sized clasts, of both local and Canadian Shield origin. The facies is massive, although distorted silt and sand wisps (Plate 4.5) are visible. Facies 6 also contains rounded to sub-rounded clay intraclasts usually < 1 cm in size.

In the New Pit West and New Pit North sections, Facies 6 unconformably overlies pre-glacial sands and gravels (Plates 4.4) (identified as such by the lack of Canadian Shield derived material). The contact is undulatory with a 20 cm amplitude. The diamicton intrudes into the underlying gravels, infilling the interstices between the gravel clasts. An orange iron-stained aureole 4 to 7 cm in thickness is seen at the pre-glacial gravel-diamicton contact (Plate 4.4). The upper contact of this aureole is sharp and discontinuous banding occurs within the aureole. In the Riverbend 1 and Old Pit sections, Facies 6 has a sharp contact with the underlying bedrock. Facies 6 is always overlain by Facies 8. The contact between the two facies is gradational.

LABORATORY DATA

THIN SECTIONS

Four thin sections were made from oriented blocks obtained from Facies 6. Thin section NPW 13 (Plate 4.6), shows the sharp contact between the iron-stained aureole and the massive diamicton. No visible differences in texture, sorting or sedimentary features were observed between these subunits. Examination of the upper part of the thin section shows alignment of elongate sand-sized particles around a 1 cm diameter clast. Diamicton pellets composed of silt and very fine sand enclosed in a clay matrix were observed in most thin sections, especially JNPW 11F,

Plate 4.4 · Pre-glacial sands and gravels overlain by the unstratified diamicton (Facies 6). The oxidized iron-stained contact (labelled 1) between the two units is seen in the center of the plate (knife handle is 9 cm).



Plate 4.5: Deformed discontinuous silt layers (indicated by arrows) within
Facies 6(knife handle is 9 cm).



Plate 4.6

Thin section intersecting the contact between the oxidized lower part of Facies 6 and the the unoxidized upper part of Facies 6. The sharp contact between the two parts is seen in the photo as the boundary in the center of the thin section. Note the similarity in texture above and below the boundary between the two parts indicating that the color difference is only a groundwater phenomenon. The scale bar is 1 cm.



JNPWT, and JNPWB. The margins of the diamicton pellets are often indistinct and diffuse but they are slightly coarser texturally and therefore observable in thin section but unlike the clay intraclasts the diamicton pellets are not directly observable in the field. No grading, foliation banding, or veining was observed in the thin sections.

MACROFABRIC

Eight macrofabric data sets were measured in Facies 6 at different localities. Their trends, eigenvalues, and eigenvectors are tabulated in Table 4.2. The trends of the data sets range over 183 degrees and as a group do not form a consistent assemblage of orientations. Rose diagrams of these macrofabrics (Fig. 4.1) indicate that data sets 2, 4, 10, are multimodal, data sets 5 and 9 are slightly multimodal, and data sets 1, 3, and 8 are unimodal. The multimodal nature of some of the fabric data sets indicates that these sets cannot be used to reliably show the clast fabric direction within the diamicton as the statistical significance of each of the modes cannot be determined (Humlum, 1981). This is because the directional trends derived from the multimodal data sets are an average resultant of all the modes in the data set which has the effect of smoothing the data. This effect of the modal averaging is best seen in data sets 4 and 10. In data set 4 the average trend is 227.4 degrees, approximately halfway between the two largest modes of, 195 and 285 degrees. Similarly data set 10 produces an average trend of 294.8 degrees, which is intermediate between the dominant modes of 283 and 325 degrees. Macrofabric strengths are indicated by their eigenvalues. The S_1 eigenvalues of the Facies 6 macrofabric data sets listed in Table 4.2 range from 0.59 to 0.87 indicating that some of the fabrics are more strongly developed than others. The average plunge is 8 degrees with minimum plunges of <1 degree and maximums of 20 degrees. Data samples 3 and 5 are imbricated to the east while the rest of the data sets are imbricated to the west.

MICROFABRICS

Two microfabrics measured from thin sections JNPWT and JNPWB, cut from the top and bottom respectively of a 6.5 cm oriented sample, showed trends of 87 and 121 degrees respectively. Rose diagrams (Fig 4.1) indicate that these

Table 4.2 Macrofabrics and Microfabrics from Facies 6.

Loc- section where the fabric was measured

Type- macrofabric or microfabric

modes- unimodal, bimodal, or multimodal

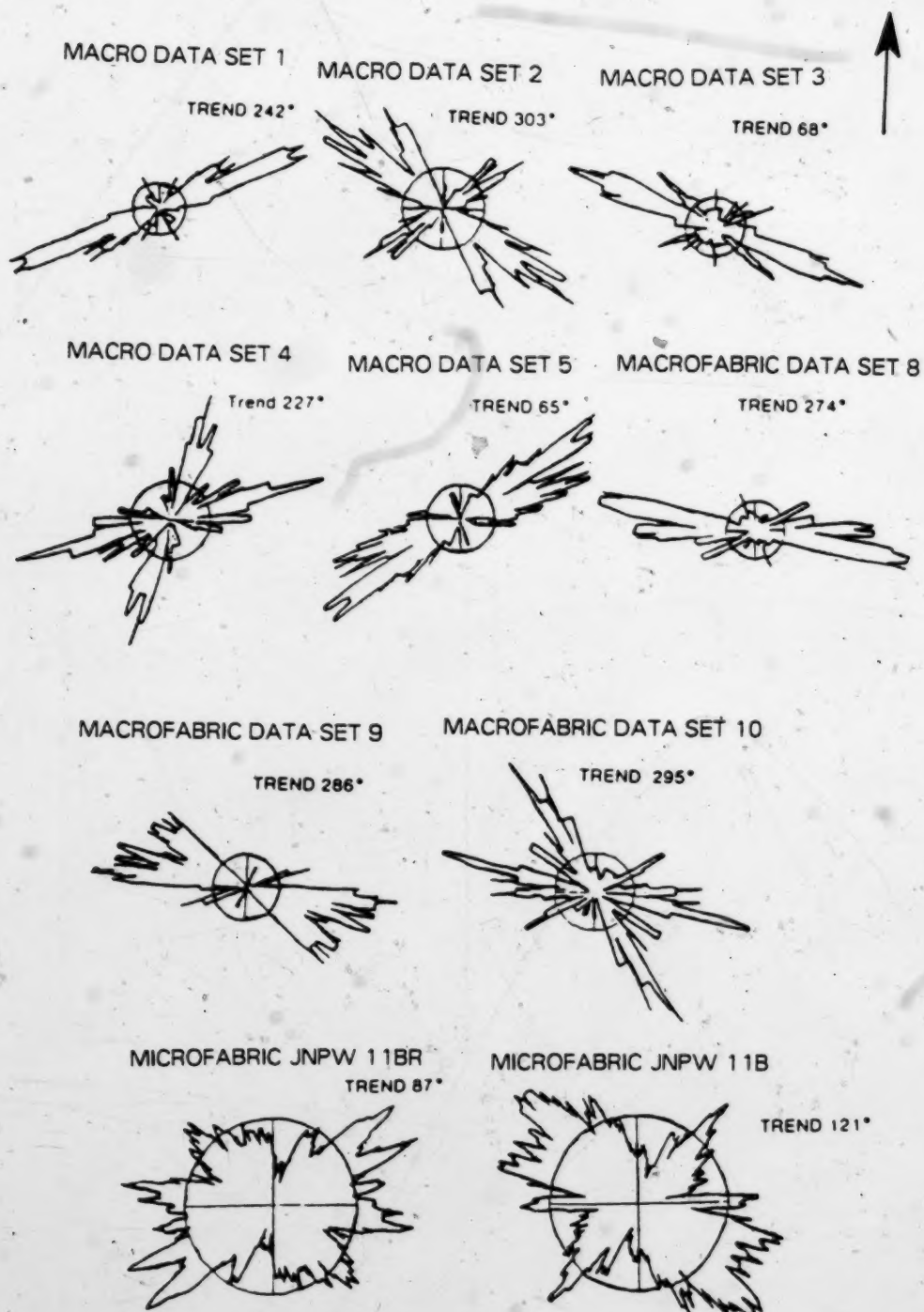
Sam S.- sample size

S_1 , S_2 , S_3 - eigenvalues

Table 4.2 Macrofabrics and microfabrics measured in Facies 6

Sample	Loc.	Type	Modes	SAM. S.	S ₁	S ₂	S ₃	Trend	Plunge
F1	NPN	Macro	1	30	.76	.19	.05	242	11
F2	NPS	Macro	Multi	35	.62	.24	.14	304	.3
F3	NPS	Macro	1	30	.73	.19	.08	68	25
F4	NPW	Macro	Multi	30	.61	.28	.10	227	8
F5	OP	Macro	Slightly bi	25	.8	.12	.08	65	13
F8	RB	Macro	1	30	.8	.17	.03	274	16
F9	RB	Macro	Multi	30	.87	.11	.02	286	14
F10	GS	Macro	Multi	30	.59	.25	.16	295	5
11T	NPW	Micro	Multi	314				86.7	
11B	NPW	Micro	Multi	267				121	

Figure 4.1 Rose diagrams of the macrofabrics and microfabrics measured in the unstratified diamicton (Facies 6). Locations of the macrofabric and microfabric samples are given in the section diagrams in Appendix 1. The fabrics are oriented on the page with north to the top of the page as shown by the north arrow.



microfabrics are multimodal.

COMBINED MACROFABRIC AND MICROFABRIC DATA

By convention, two dimensional data is given in the 0 to 180 degree range. To allow comparisons between the microfabric and macrofabric data, the macrofabric data was converted to the 0 to 180 hemisphere. The combined microfabric and macrofabric data (Table 4.2) does not form a consistent assemblage indicating that the fabric of Facies 6 is random.

TEXTURAL ANALYSIS

Textural analysis of bulk samples of Facies 6 as well as the iron-stained aureole were analyzed from the New Pit North, New pit South, New Pit West, Old Pit, and Riverbend 1 sections. This analysis indicates that Facies 6 has a sand / silt / clay texture according to the classification scheme of Shepard (1954). The iron-stained aureole is slightly coarser but still classifies as a sand / silt / clay. Grain-size parameters for Facies 6 are compiled in Table 4.3. The grain size distribution and the parameters indicate that Facies 6 is texturally polymodal and homogeneous throughout the study area (Table 4.4).

PEBBLE LITHOLOGY DATA

The pebble lithology data is given in Appendix 3. The pebble lithology indices are tabulated in Table A3.2 and plotted in Figure A1.1. The results show that the pebble lithology transformations are uniform vertically through Facies 6 in both the New Pit West and the Riverbend 1 sections.

INTERPRETATION OF FACIES 6

Several possible origins were considered for this facies including lodgement, sub-glacial meltout, sedimentation at the terminus of a stagnating ice sheet, and deposition by various processes in the glaciolacustrine environment.

ORIGIN-BY LODGEMENT

Table 3.1 lists the features associated with the lodgement process. The most common features are massive appearance; well-developed uni-modal clast fabrics; streaked, smudged, and boudinaged nondurable clasts; flat-iron shaped clasts; and ploughing of the sediment in front of clasts. Although massive lodgement tills are

Table 4.3 Textural analysis and grain size parameters of Facies 6, 8, 9, and 10.

Md Mean grain size.

Mz Median grain size.

σ_1 Standard deviation.

Sk Skewness.

Kg Kurtosis.

* one sample of graded silt sediment from the Main Section.

Table 4.3 Textural Analysis of Facies

Facies 6									
Section	Sample	sand	silt	clay	Md	Mz	ϕ	Sk	K
NPN	BMass	46	24	30	4.2	5.4	3.6	.67	.33
NPN	BMass2	45	23	31	4.8	6.0	3.6	.66	.55
NPS	TLB1	45	28	27	4.4	5.5	3.4	.67	.56
NPS	TLB2	38	33	39	7.8	6.9	3.3	.32	.64
NPS	TLB3	39	28	33	5.7	6.6	3.6	.47	.57
NPW	BMass1	46	31	23	4.0	5.3	2.5	.68	.68
NPW	TBM1	40	32	28	4.7	5.7	3.5	.61	.60
NPW	PS4	44	29	26	4.6	5.6	3.5	.61	.57
NPW	PS1	43	30	28	4.5	5.6	3.5	.62	.57
NPW	PS14	41	31	28	4.7	5.6	3.52	.59	.59
RG	T1	38	33	29	4.9	5.8	3.5	.58	.58
RB1	T1	40	30	30	5.0	5.7	3.5	.56	.58
RB1	T2	40	32	28	5.6	5.9	3.5	.46	.59
OP	T1	28	29	43	8.0	7.0	3.6	.49	.63

Facies 6, Iron-stained contact area

NPN	Fe1	45	23	32	4.9	5.7	3.5	.58	.55
NPN	Fe2	45	29	26	5.6	6.0	3.5	.42	.53
NPW	Fe1	45	33	23	4.4	5.7	3.0	.83	.69
NPW	Fe2	47	29	23	4.1	5.4	3.5	.575	.65

Facies 8

NPW	LAM1	39	33	28	5.2	4.35	3.51	.57	.63
NPW	PS11	34	37	29	6.0	6.1	3.4	.41	.62
NPW	PS9	40	31	29	3.9	5.4	3.5	.72	.58
NPW	PS6	42	31	27	4.7	5.6	3.4	.60	.60
NPW	PS8	39	29	31	5.2	5.8	3.6	.52	.57
NPW	PS5	37	33	30	5.8	6.1	3.5	.45	.59

Facies 9

NPS	PS16	33	36	31	6.5	6.3	3.5	.35	.60
NPW	PS10a	20	28	52	9.4	7.8	3.3	.04	.83
NPW	PS10b	34	43	23	5.2	6.0	3.2	.63	.38
MS	7a	30	36	34	6.7	6.5	3.4	.40	.76
MS	TURBS	5.6	66	28	7.8	7.8	1.85	1.1	1.0

Table 4.3 continued

Facies 10

Section	Sample	sand	silt	clay	Md	Mz	σ_1	Sk	Kg
NPN	TURBS1	2.3	74.7	23	6.1	6.8	2.3	.93	.82
NPN	TURBS2	3	70	26	6.2	6.9	2.5	.89	.67
NPS	TURBS3	6	65	29	7.7	7.5	2.3	.64	.78
NPS	TURBS4	3	67	30	6.6	7.2	2.6	.81	.65
NPS	TURBS5	5	63	328	6.8	7.3	2.3	.86	.67
NPS	TURBS6	3	70	26	7.8	7.6	2.5	.60	.86

Table 4.4 Cumulative grain size parameters for all facies.

Md Mean grain size.

Mz Median grain size.

σ_1 Standard deviation.

Sk Skewness.

Kg Kurtosis.

* one sample of graded silt sediment from the Main Section.

Table 4.4 Cumulative Data for all Facies

Facies	Md	Mz	σ_1	Sk ₁	Kg
Facies 6	5.3±1.3	5.9±.55	3.5±.06	.54±.16	.59±.04
Facies 6 Fe st.	4.6±.66	5.6±.30	3.4±.25	.60±.17	.60±.08
Facies 8	4.9±.60	5.5±.60	3.5±.08	.58±.09	.59±.02
Facies 10 turbs	6.9±.70	7.2±.3	2.4±.14	.78±.13	.73±.09

most common stratified lodgement tills have been described (Boulton, 1976a, Dreimanis, 1976; Müller, 1983).

Facies 6 is massive but other sedimentary features associated with lodgement are absent. The soft sediment clasts are not streaked or smudged and no ploughing was seen in front of any of the large clasts within the diamicton. Flat-iron shaped clasts with heavily striated upper surfaces were not observed. Thin sections made from this facies also lacked the veining and foliation as observed by Sitler and Chapman (1955). The lack of a consistent fabric assemblage and the multimodal fabric patterns are not consistent with the uni-modal shapes expected in a lodgement till (Marcussen, 1975, Kruger and Marcussen 1976, Boulton, 1976, Kruger, 1979). The direction of ice movement in the study area was from the North (Stalker, 1960) but the fabrics of Facies 6 indicate movement was predominantly from the east. As Facies 6 lacks the features expected within a lodgement till and possesses features which are inconsistent with a lodgement till origin the hypothesis that Facies 6 is a lodgement till is rejected.

DEPOSITION BY MELTOUT

The main features of meltout tills (Table 3.2) are their massive character with discontinuous lenses, layers, and pods of texturally or lithologically distinct sediment, clast fabrics which form consistent assemblages parallel to the ice flow direction, and their tabular geometry.

Elson (1961), and Lawson (1979), Haldorsen and Shaw (1982) state that englacial features should be preserved in a meltout till although they would be deformed and distorted by meltout of high volumes of ice. Meltout tills possess well-developed unimodal clast fabrics which form a fabric set which gives a consistent flow direction, lack continuous internal contacts, and have tabular geometries (Kruger, 1979, Lawson, 1979, Shaw, 1979, 1982, 1983).

Facies 6 is massive and has a tabular geometry but lacks any trace of remnant englacial features. The fabric data (Table 4.2), and the Rose diagrams (Fig 4.1) are bi- and multi-modal in character and do not form a consistent assemblage of fabrics which is inconsistent with a meltout origin for Facies 6. The hypothesis that Facies 6 is a meltout till is unlikely due to the lack of features commonly associated with

meltout tills but cannot be rejected entirely solely on negative evidence. But if another environment matches more closely the characteristics of Facies 6 the meltout origin should be eliminated.

DEPOSITION IN A SUBAERIAL STAGNATION ENVIRONMENT

The main features of the subaerial stagnation environment are sediment assemblages consisting of diamictons, glaciofluvial, and glaciolacustrine sediments. The proportion of each sediment type varies rapidly laterally and vertically, forming assemblages with no internal continuity. Massive silt caps, stone lines, and gravel lags are common small scale sedimentary features. The diamictons in this environment have poorly developed multimodal fabrics which do not comprise a consistent pattern related to ice flow direction.

Facies 6 possesses the poorly developed multimodal fabrics as expected in a subaerial ablation setting but the rapid variations in sediment types and the other features associated with this environment are absent. The deposition of Facies 6 from a single sediment flow is unlikely due to the distribution of this facies over an extensive area. For the above reasons it is unlikely that Facies 6 was deposited by subaerial sediment flows at the terminus of a stagnant ice sheet.

GLACIOLACUSTRINE DEPOSITION

The characteristics of glaciolacustrine diamictons (Table 3.5) are similar to diamictons deposited in the subaerial stagnation environment in that they have a random poorly-developed clast fabric which ~~does~~ not form a consistent trend parallel to the ice flow direction. But they differ in three characteristics: the presence of intraclasts, the nature of the sediments associated with them, and the continuity of the sediments in the lacustrine environment.

May (1977) states that the presence of silt and clay intraclasts diagnostically indicates deposition in a subaqueous environment. Owenshine (1970), states that the presence of till pellets is diagnostic of the ice-rafting environment, while Shaw (1982) uses the presence of blocky clay clasts to differentiate subaqueous slump and waterlain diamictons from meltout tills. Soft sediment clasts have also been widely reported in many diamictons interpreted on the basis of other sedimentary

characteristics to be waterlain diamictons (Evenson *et al.*, 1977; Gibbard, 1980; Dejong *et al.*, 1982; Dreimanis, 1982; DeJong and Martin, 1983; Eschman, 1979; Eyles and Eyles, 1983). Facies 6 has three types of intraclasts: clay clasts, pebble-cored intraclasts, and diamicton pellets. The clay clasts are similar to those described by Shaw (1982) and May (1977). The diamicton pellets with their vague diffuse boundaries observed in thin sections of Facies 6 are similar to those described by Shenk (1965), Ovenshine (1970), Link and Gostin (1981), and Visser (1983). The pebble-cored mud clasts can be interpreted as pebbles which are rolled within a debris flow thereby accumulating an outer layer of clay. These three types of intraclasts indicate that Facies 6 originated in the subaquatic environment.

The fabrics obtained from Facies 6 form a random assemblage which is consistent with that expected in a subaquatic environment (Evenson *et al.*, 1977; Gibbard, 1980). The well developed fabrics at three sites (Macrofabrics 5, 8, and 9) do not contradict this interpretation as strongly developed fabrics can occur in fluid laminarly-flowing sediment flows (Boulton, 1970; Lindsay, 1970; Lawson, 1979).

The continuity of Facies 6 over a large extent of the study area is indirect evidence that Facies 6 had to be deposited in an environment in which lateral and vertical changes were gradual such as in a lake. It is difficult to interpret Facies 6 in isolation from the facies with which it is associated as the total context of any sedimentary unit is critical to its interpretation (Frakes and Crowell, 1967, Reading, 1978). Facies associations will be considered in the Chapter 5. Despite interpretation of Facies 6 on the basis of a few sedimentary features a glaciolacustrine depositional environment is favored. Haldorsen and Shaw (1982) state that when the evidence supports one interpretation above all others that interpretation should be accepted and the inevitable uncertainty of the interpretation acknowledged.

DEPOSITIONAL PROCESSES OF FACIES 6

Now that a probable depositional environment has been identified specific depositional processes of Facies 6 in this environment will be discussed.

Anderson *et al.*, (1980a,b); Domack (1982); Wright and Anderson (1982) concluded that diamicton layers in the Ross Sea which were composed of sediment flows were laterally and vertically polymodal and homogeneous in texture. Diamicton

layers on the Ross Sea floor which were formed by the interaction of ice rafting, suspension sedimentation and bottom current winnowing were found to be bimodal and texturally heterogeneous (Anderson *et al.*, 1980a,b; Wright and Anderson 1982; Domack, 1982). The textural homogeneity and the polymodal nature of the sediments in Facies 6, indicates that this facies probably originated by subaqueous debris flow sedimentation.

The presence of intraclasts is compelling evidence of a subaquatic origin for Facies 6. Diamicton pellets are formed in the interstices between growing ice crystals (Elson, 1961; Ovenshine, 1970) and are released upon the melting of the ice. They may be introduced into the subaquatic environment from ablation of icebergs (Ovenshine, 1970), by "rain-out" from a floating ice sheet (Gibbard, 1980), or from undermelting of the margin of an ice sheet grounded in a lake (Barnett and Holdsworth, 1974). Ice-rafted deposits would have outsized clasts and clusters of clasts associated with them (Ovenshine, 1970) and are associated with other sediments such as rhythmites or lake muds (Ferrians, 1963a,b; Ovenshine, 1970; Powell, 1979, 1981). Release of diamicton pellets from beneath a slightly floating ice sheet or their release from beneath an undermelted frontal margin would form similar sedimentary deposits but as the distance between the floating ice base and the lake bottom increased the bimodal heterogeneous deposits described by Anderson *et al.*, 1980a,b would predominate.

In the study area the depth of the lake was estimated to be 75 to 100 m based on the elevation of the outlets of the lakes as published by St. Onge (1972). The shallow depth and limited areal extent of the lake when compared to modern ice shelf depths or to the Great Lakes where floating ice-shelves have been postulated (Eyles *et al.*, 1983 a; Eyles *et al.*, (1984) indicate that even a slightly floating ice margin is unlikely. A more realistic modern analogy is the eastern margin of the Barnes Ice Cap in Generator Lake, Baffin Island described by Holdsworth (1973a,b), and Barnett and Holdsworth (1974) in which the ice is grounded in 30 to 60 meters of water and has large undercut frontal aprons. Grounded ice sheets release most of their entrained debris at the grounding line by brash-ice calving producing small icebergs (Sugden and John, 1976) and by undermelting of the margin (Holdsworth,

1973a,b; Barnett and Holdsworth, 1974). Floating iceshelves and ice sheets tend to form larger icebergs which drift away from the calving front thereby distributing the sediment over a larger area. Release of the diamicton pellets and other types of entrained debris from an undermelted frontal apron would concentrate the debris in a restricted area at the grounding line where it could form cross-valley moraines (Barnett and Holdsworth, 1974). This sediment is water saturated and unstable and prone to failure resulting in its redistribution into the lake basin by sediment flows (Gustavson, 1975) and by slumps which undergo transformation into sediment flows (Morgenstern, 1967; Hampton, 1972). As the diamicton pellets can be deposited in a subaqueous setting by several different processes, their presence does not indicate a specific process but they do indicate a glaciolacustrine depositional environment.

The diamicton pellets are preserved when deposited in a subaqueous environment as subaqueous diamictons are not subjected to high overburden pressures. Easterbrook (1964) noted that glaciomarine diamictons had lower bulk densities and higher void ratios than terrestrial diamictons indicating the lower degree of compaction of the glaciomarine sediments. Terrestrial meltout tills are compressed by confining overburden and/or overlying ice giving a dense compact deposit in which the diamicton pellets are moulded into the matrix and become indistinguishable from it. Particle readjustments which the debris undergoes as it is being melted out, favor the destruction of the diamicton pellets. These particle readjustments would increase the blending of the diamicton pellets and the matrix, further blurring or completely destroying their already vague boundaries.

The fabric data obtained from this facies favors a sediment flow origin for the diamicton. The pebble fabrics of individual sediment flows are usually poorly developed (as shown by low eigenvalues) but well-developed pebble fabrics (high eigenvalues), have been reported in fluid laminarly-flowing debris flows similar to those which are postulated to have deposited Facies 6 (Bull, 1977; Boulton, 1972a; Lindsay 1970; Enos, 1977; Lawson, 1979). Only weakly-developed clast fabrics have been reported for dropstones (Schmoll, 1961). Consequently, if the diamicton formed by "rain-out" it should have only weakly developed clast fabrics as the clasts would be dropstones. The horizontal imbrication of the clasts in the fabrics is

non-diagnostic as this feature has been reported in fluid debris flows (Bull, 1964, 1977; Boulton, 1971; Lawson, 1979); with dropstones (Schmoll, 1961; Griggs and Kulm 1976; Dalland, 1976); and in meltout tills (Boulton, 1970, Lawson 1979; Shaw, 1979, 1983).

From the preceding discussion the glaciolacustrine environment is the most likely depositional setting for Facies 6. The scarcity of sedimentary features in the facies hinders identification of its depositional processes but a sediment flow origin vs a "rain-out" origin is favored due to the polymodal homogeneous texture of the facies, the presence of a few well-developed fabrics and the shallow nature of the lake which precludes a floating ice sheet.

FACIES 7, COALESCED LENSOID-SHAPED DIAMICTON WITH AGGLOMERATED TEXTURE

FIELD DESCRIPTION

The gray-black diamictons of this facies are convex-upward lensoid units which range in thickness from 0.1 to 0.5 m. Individual units have irregular gradational upper and lower contacts. Their agglomerated texture arises from the welding together of diamicton intraclasts. The diamictons are interbedded with discontinuous silt layers which are 0.1 cm to several centimeters in thickness (Plate 4.7). The silt layers are deformed and folded by the diamictons and make sharp conformable contacts with the diamictons. Blocks of diamicton are occasionally observed within the silts (Plate 4.7). The lensoid and silt layers coalesce to form 7 to 8.5 m deposits in the Main and Riverbend 2 sections. As the base of the facies extends below river level in both of the sections where this facies is exposed, the total thickness and basal contact of the facies is unknown. Facies 7 has a gradational contact with Facies 8 which overlies it in both sections.

INTERPRETATION OF FACIES 7

The diamictons are interpreted on the basis of their agglomerated textures and the preservation of large quantities of mud intraclasts to be the deposits of subaqueous slumps and debris flows which are close to their point of initiation (Smith, 1972). May (1977) and Shaw (1982) use the presence of similar clay intraclasts to identify waterlain

Plate 4.7

The diamictons and silt beds of Facies 7. The diamictons are dark gray and the silt layers are gray-green. The ice pick is 90 cm in length.



deposits and slumps. The lensoid shapes are similar to the morphology described for viscous sediment flows (Crandell, 1965; Boulton, 1970; Lawson, 1979; Pierson, 1980). The silt and clay layers represent suspension deposits which have been deposited in the lake between debris flow sedimentation events. Overriding by the sediment-gravity flows resulted in loading and deformation of the silt layers. Similar silt deposits have been described occurring between submarine sediment flows (Hicock *et al.*, 1979; McCabe *et al.*, 1984).

FACIES 8, INTERCALATED SAND LAMINAE AND DIAMICTONS WITH LARGE CLASTS

FIELD CHARACTERISTICS

GENERAL FEATURES

✓ This facies (Plates 4.8 to Plates 4.17) consists of thinly bedded diamictons separated by thin sand laminae which impart a stratified appearance to the deposits. Large clasts deform both underlying diamicton beds and sand laminae and are draped by subsequent diamicton beds and sand laminae. The facies is 1.6 to 3.8 m in thickness and has gradational contacts with facies 6 and 9 which underlie and overlie it, respectively.

Internal Features

There are three main components in this facies:

1. the diamicton beds,
2. the sand laminae,
3. the large clasts.

This facies is defined by the presence of these three main components and the interrelationships between these three components.

THE DIAMICTON BEDS

Facies 8 diamicton beds range in thickness from 1 to 23 cm (average 7.5 cm) and are approximately horizontal in attitude. The diamicton beds are uniform in thickness and traceable for tens of meters before they are obscured by colluvium. Upper and lower surfaces of individual diamicton layers are irregular on a centimeter scale with clasts projecting above and below these surfaces. Clasts make up less than 2 % of the diamicton with most clasts being less than 2 cm in diameter. The diamicton beds are ungraded and unsorted and appear to be massive but when slightly moist indistinct stratification maybe

visible. Irregular layers, lenses, or pods of texturally distinct material were not observed in any of the diamicton beds.

The diamicton beds contain four types of intraclasts:

1. mud clasts, rounded to subrounded, composed predominantly of clay,
2. rare laminated silt and clay clasts which are rounded to subrounded,
3. diamicton pellets, irregularly shaped, rounded to subrounded, composed of silt and fine sand in a clay matrix, possess diffuse boundaries with the enclosing diamicton matrix.
4. pebble-cored mud clasts, irregularly shaped clasts with pebble cores in which the clay covering is impacted onto the pebble.

The intraclasts range from 0.1 mm to 4 cm in diameter and are most often randomly distributed throughout the diamicton beds though in rare instances they occur in thin discontinuous bands. No size trends were observed between the various intraclast types.

SAND LAMINAE

Sand laminae impart stratification to Facies 8 (Plates 4.8, 4.9, 4.10). The sand laminae consist of very fine sand to coarse sand and vary in thickness from layers one or two grains to 0.5 cm and in rare cases 13 cm. Most of the thicker laminae are over-thickened by folding. Individual laminae maintain a relatively constant thickness but also thicken laterally. Laminae are traceable for tens of meters before they are covered by colluvium. Usually the sand laminae are structureless but some of the thicker laminae are horizontally laminated. The laminae have gradational to sharp contacts with underlying diamictons and sharp contacts with overlying diamictons. Thin (less than 2 mm) laminae do not truncate the diamicton below them but appear to infill the small irregularities in the diamicton surface. Laminae thicker than 2 mm have minor erosional surfaces at their bases shown by poorly developed pebble lags on the surface of the underlying diamicton. Outsized grains are common in the laminae. The sand laminae appear to be loaded by the overlying diamicton.

LARGE CLASTS

Large clasts, gravel to boulder size, are located predominantly at the top of the diamicton beds and occur singly or in clusters. The clasts possess a predominantly horizontal a-b axial plane orientation. Deformation of the diamictons and sand laminae

Plate 4.8 The diamictos and sand laminae of Facies 8 in the New Pit West. Note the thin nature of the sand laminae and diamictos, plus the minor deformation of the sand lamina and diamciton beneath the large clast in the center of the plate (knife handle is 9 cm).



Plate 4.9 Deformation beneath and drapes over large clasts within Facies 8 in the New Pit South Note the asymmetric nature of the drapes as outlined by the sand laminae. Compare the deformation and drapes in this photo to those shown in Plate 4.26 page 143. The knife handle is 10 cm.



Plate 4.10 Truncation of sand laminae by large clast in the New Pit South
(knife handle is 9 cm).



beneath these clasts is common and usually mirror the clast shape.

RELATIONSHIPS BETWEEN SAND LAMINAE, DIAMICTON BEDS, AND LARGE CLASTS

It is the sand laminae which impart the stratification to Facies 8 and allow the deformation structures beneath, and the draping over large clasts, to be observed. This deformation of several layers of diamicton and sand laminae beneath these large clasts is commonly observed (Plates 4.8, 4.9, 4.10). Sand laminae commonly terminate abruptly at large clasts which project above the diamicton surface (Plates 4.9, 4.14b, 4.16a,b). The laminae intersect the clasts at right angles with no indication of downward displacement of the laminae in the vicinity of the clast. Examination of the sand laminae beneath clasts causing deformations and beneath large clasts which project downwards from the diamicton layer in which they are enclosed, did not reveal any thickening or coarsening of the sand laminae directly below or in the vicinity of these clasts. Silt and clay films were not observed around clasts. Asymmetrical and symmetrical draping of clasts which protrude above the diamicton surface by overlying diamicton beds and sand laminae are common (Plates 4.9, 4.10). When these diamicton beds are traced laterally over the projecting clast, the diamicton may maintain its thickness over the clast, thin over the clast, or disappear (Plates 4.9, 4.10, 4.16a,b). The sand laminae associated with the drapes maintain their thickness but can be distorted over the clast (Plate 4.16b). Eight lee-side shadows and scours were observed on the west side of projecting clasts in eight separate diamicton layers.

The best example of the associations between clasts, diamicton layers, and sand laminae in facies 8 are those associated with a 18 x 14 x 10 cm clast in the New Pit South section. The clast deforms three sand and diamicton layers beneath it and is subsequently draped by several sand and diamicton layers (Fig. 4.2). In the lee of the clast the diamicton is preserved but the 1 mm sand lamina immediately overlying the clast becomes a sand filled scour, 8 x 5 x 2 cm in size, at a distance of 24 cm to the right (west) of the clast (Fig 4.2). As the sand lamina is traced further to the right (west), it is again 1 mm in thickness.

DEFORMATION WITHIN FACIES 8

In the New Pit West section several sets of sand laminae and diamictons are warped upwards into an antiform (Plate 4.11). In the center of the antiform the stratification is destroyed but in the upturned limbs the stratification is maintained. In the left limb a 7 cm

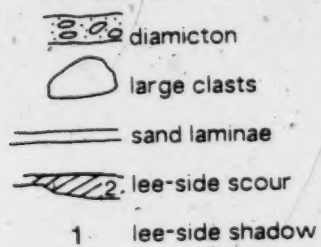
Plate 4.11

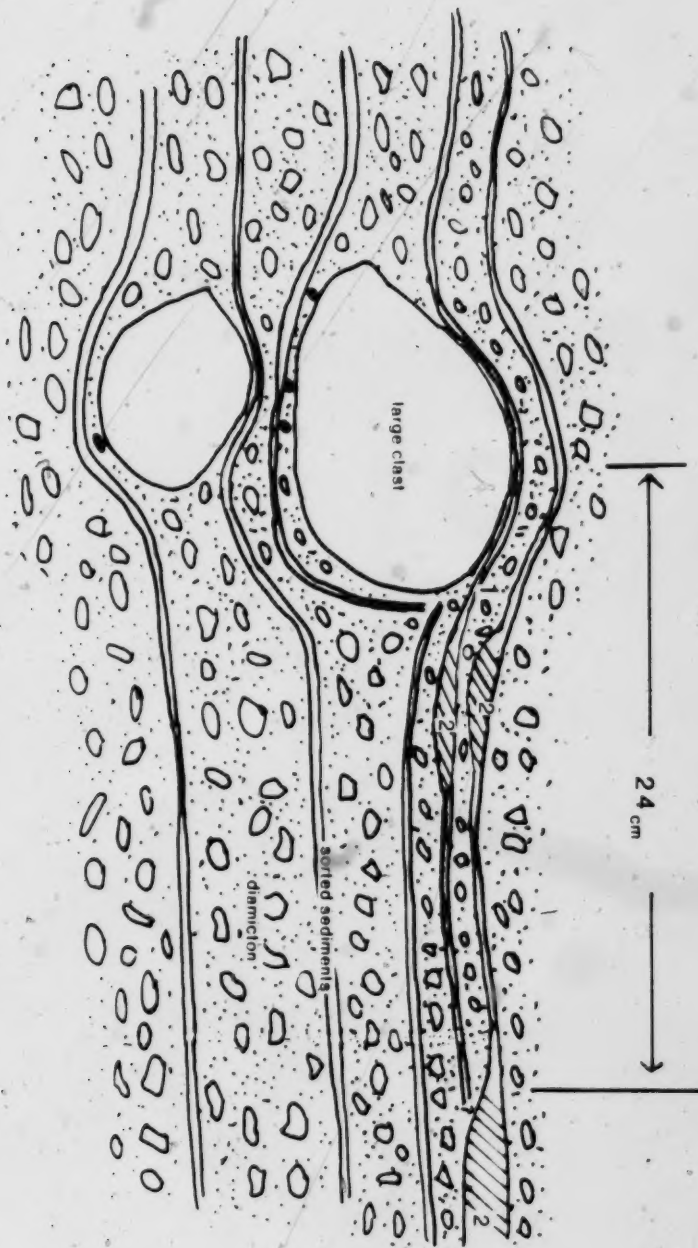
Left limb of the antiform observed in the New Pit West.

Deformation affects Facies 8 and 9. The large clast in the center right shows an inclined a-b axial plane. Deformation of the sand laminae beneath the clast mirrors the inclined a-b axial plane indicating the diamictites, sand laminae, and the stone were initially horizontal and then rotated into the present position by deformation which was probably related to diapirism.



Figure 4.2. Diagram of the deformations beneath, drape over large clasts, and lee-side shadows and scours. Scale is in cm.





clast is aligned with its a-b axial plane parallel to the displaced stratification. The deformation below the clast mirrors the long axis of the clast.

In the Main section, Facies 8 is dipping as shown in Plate 4.12 and Fig. A1.7 in Appendix 1. As in the New Pit West section the a-b axial planes of the majority of the large clasts are parallel to the bedding planes as are the deformation structures associated with these clasts, indicating that deformation of the sand and diamicton layers occurred before they were shifted into their present position. Similar dislocation of strata was seen in the Far Bridge section

In the New Pit North section the deformation of Facies 8 is more complex. The sand and diamicton strata are deformed into horizontal *en echelon* recumbent folds (Plates 4.13, 4.27a). When the sand laminae are traced laterally eastward, they intersect a north-easterly trending shear plane along which the laminae are dragged downwards (Figure A1.1, Appendix 1).

LABORATORY DATA

TEXTURAL DATA

Textural analysis of 14 samples from the diamicton beds of facies 8 shows that the diamictons classify as sand-silt-clays. Grain size parameters are listed in Table 4.3 and Table 4.4. These parameters and the sand silt clay ratios for the textural samples indicate that the diamictons of Facies 6 have a polymodal grain size distribution and are homogeneous within the facies.

PEBBLE LITHOLOGY

The results of the analysis of the pebble samples obtained from Facies 8 at the New Pit West and Riverbend 1 sections are tabulated in Appendix 3. The plots of the pebble lithology indices from samples collected in the New Pit West and Riverbend 1 sections show that the indices lithology remains constant through Facies 8.

THIN SECTION ANALYSIS

In thin section, the sand laminae appear as areas devoid of matrix material, possess sharp or gradational contacts with the underlying diamicton, and in some instances appear to infill the irregularities in the underlying diamicton surfaces (Plates 4.14a,b; 4.15a,b; 4.16a,b). The sand laminae are composed of angular to

Plate 4.12 Inclined sand laminae and diamictons of Facies 8 in the Main
Section (Knife handle is 9 cm).



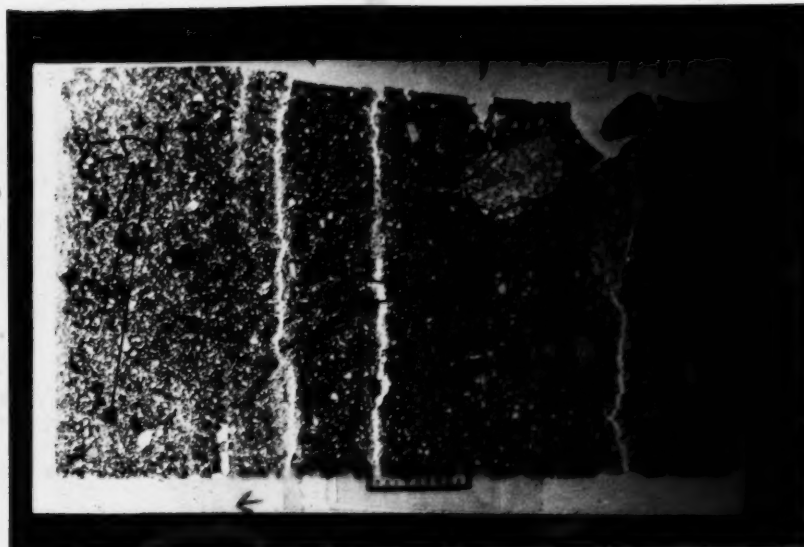
Plate 4.13

Horizontal chevron folds of sand laminae and diamictons in Facies 8 of the New Pit North. These folds probably represent drag folds produced by slumping of the overlying material upon incision of the Battle River valley. (putty knife is 20 cm).



Plate 4.14a (bottom of the page) Thin section of Facies 8 showing the contacts between the diamicton and sand laminae. Note the pebble-cored mudclast (1) and diamicton pellets (2), and large clasts (3) in the sand laminae. Note the gradational lower contact of the thick sand laminae and the sharper upper contact with the overlying diamicton. (scale bar is 1 cm).

Plate 4.14b, (top of the page) Thin section of Facies 8 showing a termination of sand laminae at a clast (arrow), and diamicton pellets (2) (scale bar is 1 cm).



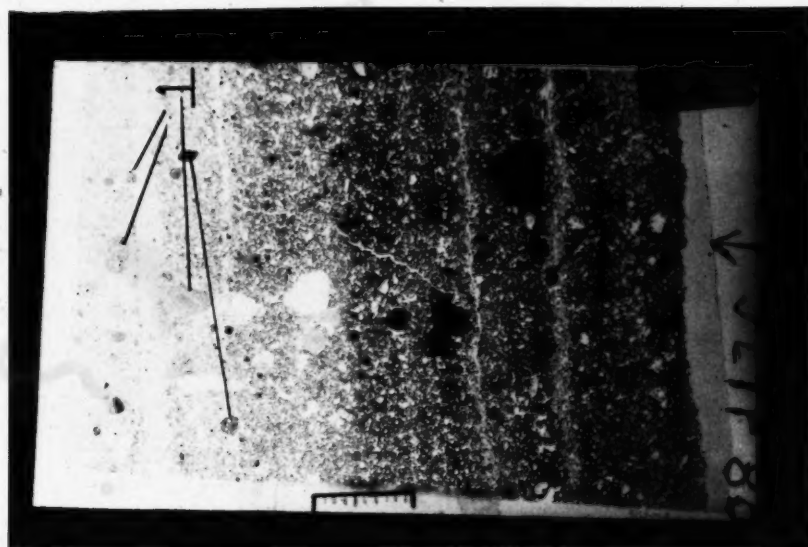
B



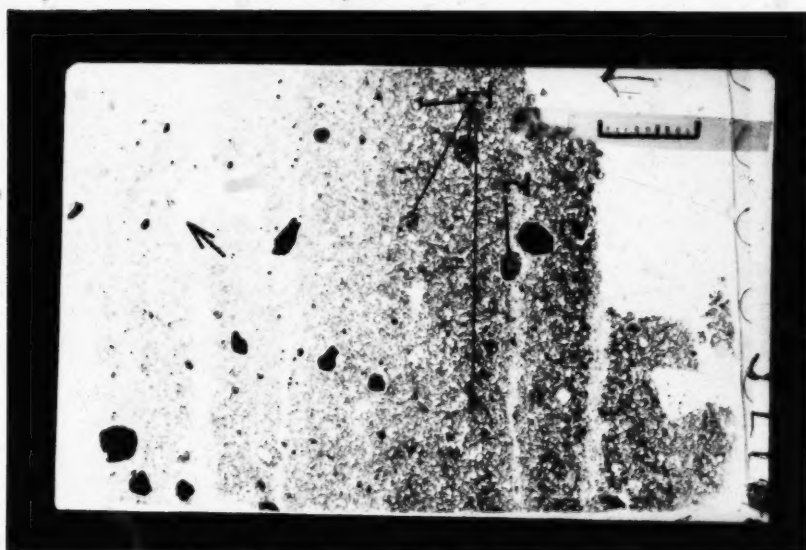
A

Plate 4.15a (bottom of page) Draping of a sand laminae over a large clast (arrow). Note the diamicton pellets (1) and silt and clay intraclast (2). (scale bar is 1 cm).

Plate 4.15b, (top of page) Note the diamicton pellets (1) within the thin section (scale bar is 1 cm).



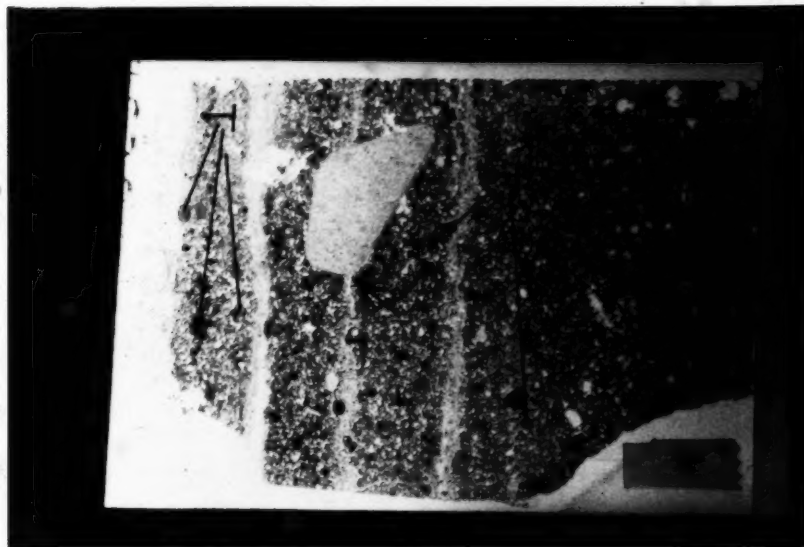
B



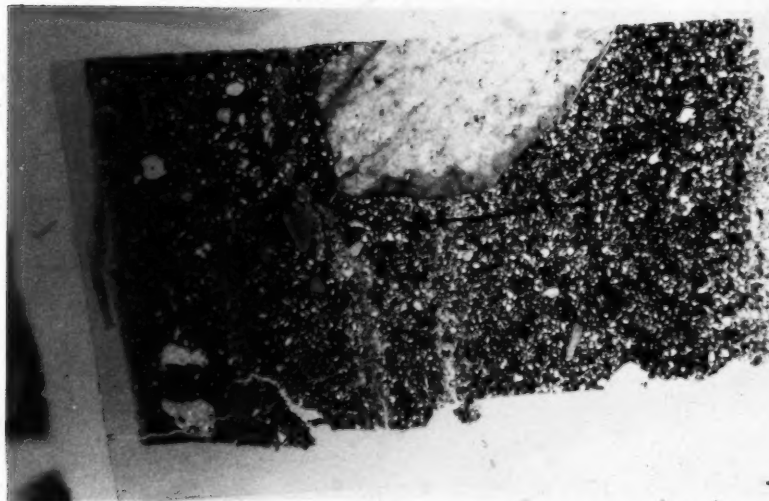
A

Plate 4.16a (bottom of page). Thin section of Facies 8 showing asymmetric drape over clast (arrow). Note the diamictite pellets (1) (scale bar is 1 cm in length).

Plate 4.16b (top of page). Termination of a sand lamina at a large clast. Note the diamictite pellets (1) and the silt-clay intraclast (2), scale bar is 1 cm.



B



A

subrounded sand grains with minor amounts of silt. Infrequently larger particles are seen suspended in the thicker sand laminae (Plate 4: 14, 4.15). Mineralogy of the sands is 90 % quartz, 8 % feldspar, and 2 % heavy mineral and exotic grains. The overlying diamicton appears to depress and deform the sand lamina directly beneath it (Plate 4.14a,b; 4.15a,b). No stratification was observed in the sand laminae in thin section. Thin sections of a 5 cm thick sand lamina from the New Pit West and its enclosing diamicton showed that it was composed of a complex set of dewatering structures (Plate 4.17). Sand laminae in thin sections can terminate abruptly at large clasts or drape clasts in ways similar to those observed in the field (Plates 4.14b, 4.15a, 4.16a,b). Small lee-side shadows and scours were also observed (Plate 4.15b). No veining, foliation, or evidence of differential compaction was observed in any of the thin sections. Clasts observed in thin section which projected from the base of a diamicton formed a depression in the sand laminae below them but no thickening of the sand laminae or coarsening of the grain-size was seen in these locations (Plate 4.16a,b).

DIAMICTON LAYERS

In most thin sections, the diamicton beds appear to be unsorted and ungraded but in some thin sections poorly defined textural banding is observable within the diamicton layers. This may be related to the indistinct stratification observed in the field sections. The four intraclast types observed in the field are also visible in thin section (Plates 4.14a,b; 4.15a,b; 4.16a,b).

FABRIC DATA

Two macrofabric and six microfabric data sets were measured in Facies 8 of the New Pit West (Fig 4.3). Since the thinness of the diamicton layers precluded the measurement of separate clast fabrics within them, the two macrofabrics collected spanned several diamicton layers above and below a marker bed. The trends of the two macrofabrics are 266 and 287 degrees (Fig 4.2) but the trends (Table 4.5) may be inaccurate as rose diagrams (Fig 4.3) show that the data sets are multimodal. The plunges of the macrofabrics are 6 and 12 degrees respectively.

Microfabric data from closely spaced thin diamicton layers was obtained by using horizontally cut thin sections. The microfabrics were multimodal in character

Plate 4.17 Thin section showing dewatering structures in Facies 8 of the
New Pit West (scale bar is 1 cm).

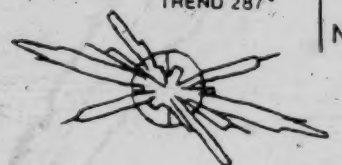


Figure 4.3 Rose diagrams of the macrofabrics and microfabrics measured in Facies 8. Location of samples given in the section diagrams in Appendix 1. The fabrics are oriented on the page with north to the top of the page as shown by the north arrow.

MACRO DATA SET 6
TREND 266°



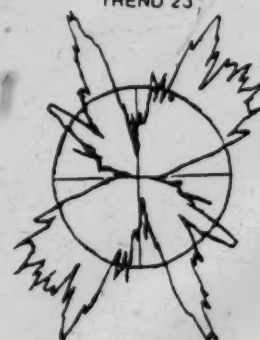
MACROFABRIC DATA SET 7
TREND 287°



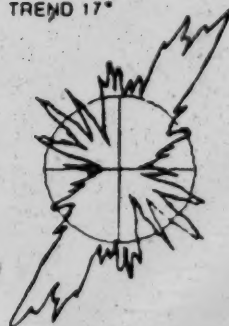
MICROFABRIC JL 1A
TREND 37°



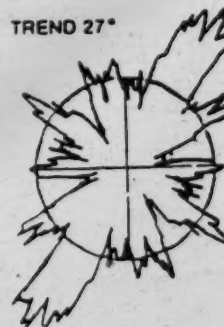
MICROFABRIC JL 1B
TREND 23°



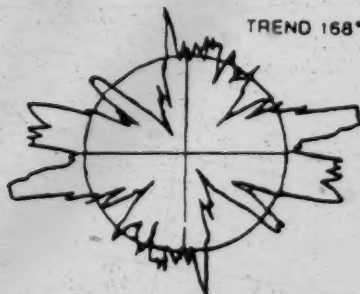
MICROFABRIC JL 1C
TREND 17°



MICROFABRIC JL 1D
TREND 27°



MICROFABRIC JNPW 10T
TREND 168°



MICROFABRIC JNPW 10B
TREND 94°



Table 4.5 Macrofabrics and Microfabrics from Facies 8.

Loc- section where the fabric was measured

Type- macrofabric or microfabric

modes- unimodal, bimodal, or multimodal

Sam S.- sample size

S_1 , S_2 , S_3 - eigenvalues

Table 4.5 Macrofabrics and Microfabrics from Facies 8

Sample	Loc.	Type	Modes	Sam. S.	S ₁	S ₂	S ₃	Trend	Plunge
F6	NPW	Macro	one	26	.69	.22	.09	267	6
F7	NPW	Macro	multi	31	.64	.26	.09	287	12
JL 1A	NPW	Micro	multi	144				37	
JL 1B	NPW	Micro	multi	169				23	
JL 1C	NPW	Micro	multi	228				17	
JL 1D	NPW	Micro	multi	183				27	
10T	NPW	Micro	multi	295				168	
10B	NPW	Micro	multi	267				94	

(Fig. 4.3). Microfabrics of data set 1 were obtained from 4 diamicton beds which spanned a vertical interval of 6.5 cm. Their trends show a close correspondence (Table 4.5) with a variation of only 20 degrees. Data group 2, obtained from two diamicton layers 4.5 cm apart shows a 74 degree spread between the two samples (Table 4.5) indicating a lack of consistency between the two microfabrics. No consistent trend is observed between the two sets of microfabric data and no consistent orientation is observed when the microfabrics and macrofabrics are combined.

SUMMARY OF THE SEDIMENTARY FEATURES OF FACIES 8

Facies 8 is a stratified diamicton in which large clasts predominantly occur above the sand laminae at the top of the underlying diamicton layers. The clasts deform the diamictons and sand laminae below them, and are draped by subsequent diamictons. Also associated with the outsized clasts are lee-side shadows and scours which occur only on the west sides of the clasts. The sand laminae are thin, and have erosive lower contacts and sharp conformable upper contacts. They are usually structureless but thicker ones can be planar bedded. Outsized grains are observed within the sand laminae. The sand laminae impart the stratification to the facies and cause the deformations and drapes associated with the outsized clasts to be visible. The diamicton layers are thin, uniform in thickness, with homogenous polymodal textures, and contain four varieties of intraclasts. Micro- and macrofabrics are multimodal and form a random set of orientations.

INTERPRETATION OF FACIES 8

A discussion of several possible origins for Facies 8 will follow using the same approach as used for Facies 6.

FORMATION OF FACIES 8 BY A LODGEMENT PROCESS

Lodgement tills are commonly believed to be massive in character (Boulton, 1976; Shaw, 1976) but Dreimanis (1976) and Müller (1983), describe lodgement tills that are stratified. The stratification described by Dreimanis (1976), is caused by shearing associated with the lodgement process. Müller (1983), attributes the formation of laminae of sorted sediments to dewatering upon collapse of the till

structure during the lodgement process and to washing at the ice-sediment interface by thin films of flowing water. He believes both processes can be active within a single lodgement till. These processes form drapes over clasts due to differential subsidence, abrupt terminations at clasts due to blockage of the flowing water layer, and silt and clay films around clasts due to water convergence.

In Facies 8 the intraclasts contained in the diamictons are not streaked, smudged, or boudinaged and therefore have not undergone shearing which is a necessary part of the lodgement process (Table 3.1). On a microscopic scale the veining and foliation described by Sitler and Chapman (1955); was not observed in any of the thin sections from this facies. Examination with the S.E.M. showed that the diamictons had an open card-house structure indicating that they had not undergone shearing which would have aligned the particles.

Facies 8 superficially resembles the lodgement till described by Müller (1983), as it is stratified, the sand laminae drape larger clasts, and abrupt terminations of the sand laminae by the clasts are also common and water flowing at the ice-sediment interface forms some of the features. But there are significant differences. As previously mentioned there are no signs of shearing associated with the plastering-on process of lodgement, which would smudge, streak-out, and destroy the soft intraclasts of Facies 8. Facies 8 contains mirror drapes beneath large clasts and lee-side shadows and scours features not cited by Müller (1983). If the deformations were caused by differential compaction then the drapes should all be symmetrical, but many of them (for example Plate 4.9) are asymmetrical indicating that differential compaction did not form them.

The characteristics of the sand laminae such as the loading, their gradational contacts, the presence of outsized grains, and the sedimentary structures observed in some of the laminae favor sedimentary processes in which flowing water was involved. The presence of the lee-side shadows and scours and the pebble lags indicates that the currents were stronger than those expected within a thin water layer at the sediment-ice interface. The depth of flow is also greater than that expected for a sediment-ice contact water layer.

Fabric studies in lodgement tills have shown them to have well-developed unimodal clast fabrics which as a set give a consistent regional trend. Microfabrics have been shown to closely correlate to the macrofabrics (Harrison, 1957; Gravenor, 1969; Evenson, 1971; Jackson, 1973). The macrofabrics of Facies 8, however are not consistently unimodal and form a fabric set which lacks a consistent orientation parallel to the ice flow direction. The orientations of the microfabrics and macrofabrics are not consistent. This variance in fabric orientation and style is not consistent with a lodgement origin.

Lack of shear features, absence of well-developed unimodal fabrics, and the presence of sedimentary structures not readily produced by the lodgement process indicate that Facies 8 is not a lodgement till.

FORMATION BY MELTOUT PROCESSES

Meltout tills are normally considered to be massive in character but stratified diamictos have also been interpreted as meltout tills (Shaw, 1977a,b, 1979, 1983). Facies 8 superficially resembles these stratified tills in that it possesses diamicton layers intercalated with thin sand laminae, which drape clasts projecting above the diamicton surface. They also terminate abruptly at clasts. Shaw's (1979) interpretation of Sveg Tills as meltout tills is tied to the mechanism of formation of the sand laminae and interpretation of the inter-relationships between the sand laminae, diamictos and large clasts. Interpretation of Facies 8 as a meltout till will similarly be greatly dependent upon the interpretation of the genesis of the sand laminae and their relationship with the diamicton beds and large clasts. If Facies 8 represents a meltout till the sand laminae could have three origins:

1. The sand laminae could be contained in blocks of sediment which are eroded, entrained, and subsequently released from the ice by meltout,
2. They could be carried as separate sediment bands within the ice and intercalated with the diamictos upon meltout,
3. they could form during the meltout process itself.

Meltout tills formed by release of entrained debris from stagnant ice have been described in detail by Lawson (1979). He observed that debris was distributed in irregular and discontinuous bands, layers, and pods throughout the ice. This

erratic distribution of debris causes folding and deformation of debris bands upon meltout due to differential subsidence. Elson (1961) and Haldorsen and Shaw (1982) concur with Lawson (1979) that meltout tills should possess deformation structures and texturally or lithologically distinct pods of sediment. The resulting meltout deposit was observed to possess a tabular geometry, be massive in character with pods of texturally or lithologically distinct material, lack continuous internal contacts, and possess well-developed fabrics which form a consistent assemblage which parallels the ice flow direction. Facies 8 differs greatly from the criteria of Lawson (1979). It is stratified not massive, possesses numerous well-defined continuous internal contacts, does not have well-developed fabrics which form a consistent fabric assemblage, and lacks discontinuous irregularly distributed pods and lenses of distinct sediment types. Studies on the distribution of debris in modern glaciers and ice sheets (Table 3.3) indicate that the irregular debris distribution described by Lawson (1979) is common to all modern ice sheets and ice masses. The sedimentary features of Facies 8 are preserved over a large areal extent with no sign of deformation or disruption. This would require an extremely uniform distribution of debris within the ice which is contradicted by studies of debris distribution within modern ice sheets, ice caps and glaciers (Table 3.3). A uniform distribution of debris maybe possible over short distances but it is unlikely that this could occur for the extent of Facies 8. Therefore as Facies 8 could not form from the meltout of ice which contained large blocks of diamicton intercalated with sand laminae.

The second possibility that the sand laminae and diamicton layers were carried as discrete sediment units in the ice and melted out intact as horizontally intercalated beds is also untenable. Observations by Lawson (1979) showed that beds of noncohesive sediments which possessed sharp contacts while in the ice; possessed blurred indistinct contacts in the deposit which resulted from their melting-out. The sand laminae of Facies 8, even those only a few grains thick, possess sharp distinct contacts with the surrounding diamicton layers. Meltout of such thin non-cohesive layers should at least blurr the contacts and would be more likely to totally destroy them as preservation of thin debris bands would require an unrealistically uniform distribution of debris over a large areal extent and particle

readjustments during meltout would tend to disrupt such fine bands as observed by Lawson (1979). The features of the sands such as pebble lags and lee-side shadows and scours indicate an intimate association between the sands and the diamictons which would not be found if both originated separately and were then joined. The lack of a consistent fabric direction also lessens the interpretation that this is a meltout till which was created by release of entrained blocks of debris.

It is not possible for the sands to have originated by some mechanism during the meltout process such as modelled by Shaw (1979). In Shaw's model the sand laminae are deposited in cavities and along foliations by flowing water released during the meltout of debris-poor ice layers. The water does not come in contact with the diamicton sediments and the drapes are formed by differential subsidence around clasts which project above the diamicton surface. The model does not explain the source of the sands nor does it account for the lack of thermokarsting which should accompany water flowing through ice.

As the flowing water deposits the sands in ice cavities the erosional features of Facies 8 such as the pebble lags and the lee-side shadows and scours would not be able to form. The abrupt terminations of the sand laminae at clasts which intersect foliation planes (Shaw, 1979) are downwarped by differential subsidence but those of Facies 8 (Plates 4.10, 4.14b, 4.16a,b) intersect the clasts at right angles indicating that subsidence which would occur in a meltout till had not taken place. Deformations beneath large clasts common in Facies 8 were not cited by Shaw (1979). Shaw (1982, 1983) describes boulder scours formed beneath boulders interpreted to be suspended from ice into englacial streams which are flowing beneath the boulder. The areas beneath the clasts are scoured and the sands coarsened in texture. These features were not observed in the sands beneath large clasts regardless whether the clast had deformed the sand and diamicton layers below it or not.

Fabrics measured in meltout tills by Lawson (1979, 1981), and fabrics measured in diamictons interpreted to be meltout tills (Shaw, 1979, 1983) were well-developed and formed a consistent fabric assemblage parallel to ice flow. Lawson (1979) states that meltout tills with random fabrics will be found if

differential overburden pressures cause disruption of the englacial fabric. The high degree of preservation of the sedimentary features of Facies 8 indicates that little disruption had occurred and therefore if this was a meltout till be well-developed fabrics forming a consistent assemblage must be present. Finally, if the sand laminae were formed during the meltout process it is unlikely that they would be able to survive meltout without disruption or blurring of their boundaries due to the irregular debris distribution in the ice and particle readjustments which occur during meltout. Although not present at the sections used by Shaw (1979) to develop his model of meltout other Sveg Till sections are complexly folded and deformed (Shaw, 1979).

The features observed in Facies 8 do not fit the models of meltout tills as outlined. The nature of the fabric, the continuous undeformed internal contacts, and the interrelationships between the large clasts, sand laminae, and diamicton layers indicate that Facies 8 is unlikely to be a meltout till.

DEPOSITION IN A SUBAERIAL STAGNATION ENVIRONMENT

Facies 8 has a large degree of aerial continuity and repetition of strata, characteristics which are incompatible with the rapid sediment assemblage variation expected in a subaerial stagnation environment. The thin continuous sand laminae are also not associated with this environment. The deformations of the strata below large clasts (Plate 4.9) appears to be formed by vertical impact of the clasts which is unlikely to occur in a subaerial situation. The lee-side shadows and scours could be produced in a sub-aerial environment, but it is difficult for a subaerial stream to form lee-side shadows and scours without creating pebble lags or depositing recognizable glaciofluvial sediments. It is unlikely that the features associated with Facies 8 were produced in a subaerial environment.

Rapid vertical and horizontal variations in sediment type, gravel lags, boulder lines, and poorly developed fabrics which form a random fabric set that does not match the ice flow direction are features expected in a subaerial stagnation environment (Table 3.4). These features are absent in Facies 8 with the exception of a random set of poorly-developed fabrics. Absence of features is usually a weak argument but the absence of most of the features associated with a subaerial stagnation environment and substitution of a suite of features which cannot be

readily explained as products of this environment indicates that this is not the depositional environment of Facies 8.

The formation of recumbent folds by movement of the overlying strata has been described by McKee *et al.* (1963a, b). Similar folded strata were investigated by Crowell (1957) who discussed the difficulties of separating deposits formed by slumping from those deposited by ice sheets. Miller (1963) describes similar folded strata within the glaciolacustrine sediments of the Coppermine River in Alaska.

FORMATION OF FACIES 8 IN A SUBAQUEOUS ENVIRONMENT

The sedimentary features of Facies 8 can all be produced by depositional processes active in a subaquatic environment. In addition to the intraclast types of Facies 6, Facies 8 contains silt and clay laminated intraclasts. The diamicton pellets, pebble-cored mudclasts, and mudclasts are indicative of a subaquatic environment. The laminated silt and clay intraclasts are interpreted as rip-up clasts of sediments initially deposited in quiet water, then eroded and transported by sediment flows, and subsequently deposited when the flow stopped. Silt and clay intraclasts of this type have been described from the Catfish Creek sections by Evenson *et al.* (1977) and Gibbard (1980). Preservation of friable materials in sediment flows has been reported by Enos, 1977. Subaqueous debris flow deposits are polymodal, homogeneous, and possess sharp continuous internal contacts (Kurtz and Anderson, 1979). Fluid debris flows are uniform in thickness (Bull, 1977, Fisher, 1971, Lawson, 1979,). A sediment flow origin is also suggested by load structures present in the sand laminae underlying diamicton beds.

When the nature of the lake is considered the possibility that "rain-out" from floating ice deposited the sediments is unlikely. Data on the elevations of glacial lake outlets in the study area (St. Onge, 1972) and lines of closure on topographic maps indicate that the lake was of limited areal extent and shallow. These factors favor grounded rather than floating ice. Grounded ice wastes by brash ice production which concentrates the debris at the grounding line (Sugden and John, 1976). The small icebergs produced by brash ice calving are capable of carrying boulders and clasts which will subsequently be released, settle through the water column, and deform the bottom sediments upon impact. The grounded ice could also release its

debris from undermelted grounded ice margins (Holdsworth, 1973a,b, Barnett and Holdsworth, 1974). The brash ice calving and undermelting release the bulk of the debris entrained in the ice at or near the grounding line. Subsequent slumping of the underconsolidated oversaturated sediment redistributes it into the lake basin.

Sand laminae formation in a subaqueous setting can occur by two separate processes. The thin (<1 cm) structureless laminae with larger grains dispersed within them and pebble lags at their base may be produced through winnowing of the surface of the diamictos (Kurtz and Anderson, 1979; Anderson *et al.*, 1980a, 1980b; Domack 1982). The degree of winnowing controls the sedimentary features. The deposit can be largely removed leaving only a lag deposit, or minor erosion can form a thin sand layer. Winnowing of the diamicton surface around clasts projecting above the diamicton tops accounts for the abrupt terminations of the sand laminae at clasts. The lee-side shadows and scours observed in association with the outsized clasts can also be formed by bottom currents. When bottom currents encounter a projecting clast the current diverges over and around the clast and reconverges down current of the clast (Fig 4.2). At the point of divergence (the lee of the clast) the diamicton is not heavily winnowed by the current but at the point of flow convergence the diamicton is scoured. In Facies 8 the shadows and scours are consistently located on the West side of the clasts indicating a predominantly westerly current flow. Thicker horizontally laminated sand laminae (>1 cm) of coarse sand were probably deposited by turbidity currents.

As stated in the discussion on meltout formation of Facies 8, determination of the means of formation of the sand laminae is crucial to the interpretation of Facies 8. Frakes and Crowell (1967) state that if the nature of the interbeds can be determined, the genesis of the diamicton is easily established. Since the sand laminae are best interpreted as the products of lake bottom currents and turbidity currents, the diamictos with which they are interbedded must also have a subaquatic origin.

As most of the large clasts occur at the top of the diamictos and deform both the sand laminae and the diamicton layers below them, the clasts must have been deposited after the formation of the sand laminae. The nature of the deformation structures below the clasts indicates that they are dropstones and do

not represent inverse grading developed by dispersive pressure within the moving debris flows. These clasts are also draped by subsequent sand and diamicton units. The deformation structures and drapes associated with the outsized clasts match the descriptions and photographs of dropstones contained in the literature (Hardy and Legget, 1960; Banerjee, 1973; Eschman, 1979; Huddart, 1983; Young, 1970). The sharp abrupt terminations of the sand laminae around the outsized clasts can also be produced by the dropstone piercing the bedding. Owenshine (1970) states that clusters of clasts are another characteristic of iceberg-rafted material.

The formation of drapes can also be explained using a subaquatic debris flow mechanism. If a clast projects above the surface of the diamicton thin fluid sediment flows may deposit around it. As sediment flows are viscous they can flow over a clast and maintain their thickness causing the clast to be draped as shown in (Figures 4.2 and 4.4).

The fabric data is the random pattern expected of debris flows and rain-out deposits. The slight consistency observed in the JL 1A through JL 1D fabric samples may result from consistent flow down a slope (Bull, 1977; Huddart, 1983; Haldorsen and Shaw, 1982).

SUMMARY OF THE DEPOSITION OF FACIES 8

Consideration of the characteristics of Facies 8 indicates that the best interpretation that the facies was deposited in a glaciolacustrine setting by the interaction of debris flows, ice-rafting, bottom currents and turbidity currents. The diamictons of the facies are more likely to be deposited by subaquatic debris flows than by "rain-out" because their homogeneous polymodal texture, sharp continuous contacts, the loading of the sand laminae, and the inclusion of the laminated rip-up intraclasts within the diamicton. Bottom and turbidity currents can account for all the characteristics of the sand laminae. A dropstone origin for the large clasts is supported by the location of the clasts above the sand laminae on top of the diamicton layers, their occurrence in clusters, the piercing and deformation of the strata below the clasts, and the draping of the diamicton layers and sand laminae over the clasts.

DEPOSITION OF FACIES 8

Facies 8 is polygenetic in nature with many different mechanisms forming its sedimentary features. Figure 4.4, illustrates the model proposed for the formation of these features. Initially a thin fluid sediment flow deposits an ungraded unsorted diamicton which due to its fluid nature has horizontally oriented clasts. The fluid nature of the flow also causes the deposit to be sheet-like and thin with minor surface irregularities and clasts projecting from its upper surface. The upper surface of the sediment flow is subjected to sediment input from icebergs, overflows and interflows, turbidity currents, and winnowing by lacustrine bottom currents. The currents erode the upper surfaces of the diamictons removing the finer sediments and leaving poorly-developed discontinuous pebble lags and massive structureless sands. Some of the flows load the underlying sand laminae to minor extents. Large clasts released from drifting icebergs settle through the water column and deform the sand laminae and diamicton layers upon impact. If a clast is thicker than the next debris flow, the flow will surround the clast on all sides due to its fluid nature and part of the clast will remain exposed above the flow surface. Bottom currents winnow the sediment flow top around projecting clasts forming sand laminae which terminate at right angles to the clast. Large clasts cause divergence of flow in the bottom currents as they pass the clast. Where the current flow converges, the diamicton is scoured and a thick lens of sand is deposited. Thicker and more viscous flows are able to flow over the large clast and maintain their thickness, forming drapes over the clast. Asymmetric drapes can form if the viscosity of the flow is sufficient for the flow to move unevenly over the clast causing the proximal part of the clast to be covered by a thicker deposit than the distal part of the clast. The winnowing of the diamicton surface leaves a thin sand lag on top of the draping debris flow which is preserved beneath the next debris flow thereby outlining the drape. Sedimentation continues in this manner with sporadic turbidity currents depositing bedded sands on top of the diamicton.

FACIES 9, THE INTERCALATED DIAMICTON, SILT LAMINAE, AND LARGE CLASTS

FIELD DESCRIPTION

GENERAL APPEARANCE

Figure 4.4

Formation of Facies 8 by interlayering of fluid laminarly-flowing

diamictos with sand laminae. The diamictos and sand laminae

are disrupted by many dropstone deformation structures. Time

1. A single sediment flow in which dropstones have fallen but deformations are unobservable due to the lack of sand laminae.

Time 2. Formation of sand laminae by winnowing of the

diamicton surface by bottom currents abrupt termination of sand

laminae at the clast's margins. Time 3. Addition of another fluid

sediment flow around the dropstone forming the abrupt

terminations of the diamicton at the clast's margins. Time 4.

Impact of dropstone deforms the diamicton and sand laminae

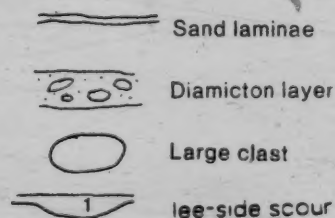
beneath it. Time 5. Renewed debris flow sedimentation covers

the large clast, bottom currents form lee-side shadow and

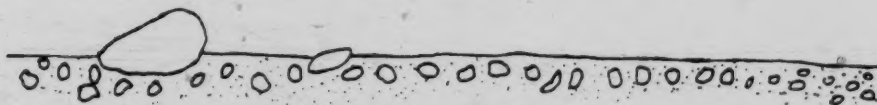
scours behind the clast. Time 6. Sediment flow deposition,

deposition of stratified sand laminae by a proximal turbidity

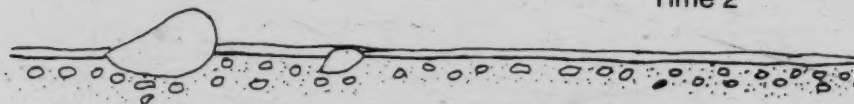
underflow.



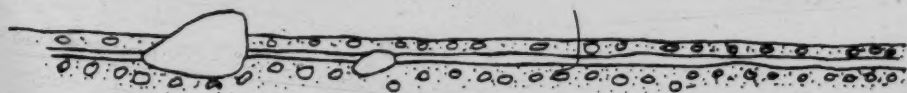
Time 1



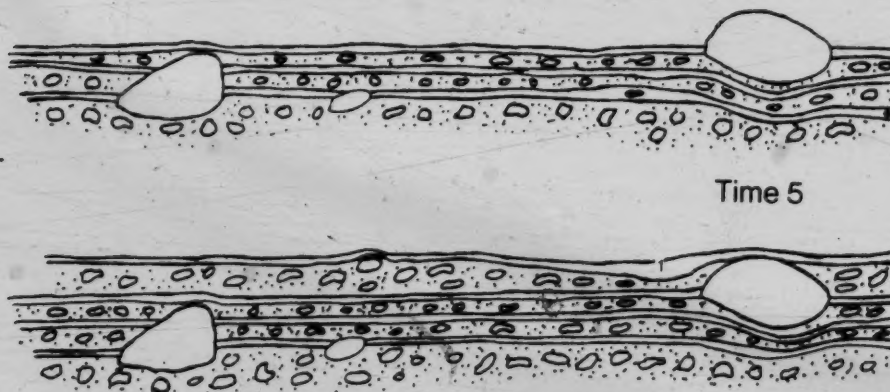
Time 2



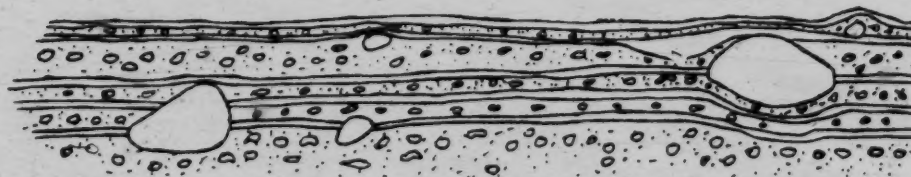
Time 3



Time 5



Time 6



Facies 9 consists of thinly bedded diamictons intercalated with silt laminae. Large clasts are present predominantly at the top of the diamicton beds (Plate 4.18). Facies 9 has gradational contacts with Facies 8 and 10 which respectively underlie and overlie it. The main features of Facies 9 are the diamicton beds, the large clasts, and the silt laminae. It is the presence of silt laminae which allows Facies 9 to be distinguished from Facies 8. Due to the gradational nature of its lower contact the base of Facies 9 was arbitrarily taken at the appearance of the first continuous silt laminae. A few sand laminae were observed in the basal part of the Facies in association with the silt laminae but the silt laminae predominate. It is the silt laminae which replace the sand laminae of Facies 8.

DIAMICTON BEDS

The diamictons of this facies are approximately horizontal in attitude and vary in thickness from 4 to 12 cm with the thickness remaining constant for the tens of meters that they are exposed. The upper and lower surfaces of the diamicton beds have irregular contacts with the silt layers. The same four varieties of intraclasts observed in Facies 8 are more abundant in Facies 9 (Plate 4.19). Laminated silt and clay intraclasts are particularly noticeable.

SILT LAMINAE

The silt laminae vary from 0.1 to 0.5 cm in thickness. The thickness remains relatively constant throughout the length of the exposure (tens of meters). The silt laminae are generally massive but clay partings were occasionally observed. Often the silt laminae show load features which are associated with the overlying diamicton layer and are broken and disrupted giving the laminae the appearance of being formed of collections of silt clasts. Sediment blocks plucked from the silt laminae were observed within the base of the overlying diamicton layer. Unbroken silt laminae appear to infill the irregular upper surface of the diamicton underlying them.

LARGE CLASTS

These clasts have predominantly horizontal to sub-horizontal a-b axial plane orientations which parallel the stratification in the unit (Plate 4.18). Most of the clasts are located at the top of the diamicton beds (Plate 4.18).

INTER-RELATIONSHIPS BETWEEN THE COMPONENTS OF FACIES 9

The same type of deformations as seen in Facies 8 were observed in Facies 9. The abrupt

Plate 4.18 Silt laminae intercalated with diamictons and interrupted by horizontally lying clasts. The silt laminae can be seen to drape over the center (arrow) clast and be deformed by the top center clast (arrow). Note also the right angle intersection of the silt layer and the clast immediately to the right of the knife handle. (knife handle 9 cm).



Plate 4.19 Facies 9 in the oxidized upper part of the New Pit South. The horizontal breaks occur at silt laminae. The light colored clasts (arrows) in the plate are mud and diamicton clasts which dry lighter than the surrounding diamicton (knife handle is 9 cm).



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terminations and drapes observed in Facies 8 are also present in this facies (Plates 4.18, 4.20). Lee-side shadows and scours are absent in Facies 9.

DISLOCATIONS WITHIN FACIES 9

In the Main Section, the normally horizontal strata of Facies 9 are inclined in the same manner as Facies 8 which underlies it. The large clasts and the deformations below them are also inclined indicating that they have been rotated into this position subsequent to deposition (Plate 4.20, 4.21).

In the Main Section Facies 9 occurs at approximately 9 m elevation above the river level. In the Kettle section, which is contiguous with the Main Section, Facies 9 occurs at river level. The Kettle section is bounded laterally by high angle normal faults, but the strata within the section are flat lying and undeformed despite the nine meter displacement (Plate 4.21).

LABORATORY ANALYSIS

TEXTURE

Four textural samples obtained from three diamicton and one silt layer from Facies 9 were analyzed. The analysis of the diamictons indicates that they are finer than the diamictons of Facies 6 or 8. The finer texture of the diamictons was also noted in thin sections of the unit. The grain size parameters are given in Table 4.3.

THIN SECTIONS

No grading or sorting was observed in the diamicton beds. The silt laminae appeared massive and contain load features related to the overlying diamicton. The intraclasts observed in the field were also observed in thin section.

PEBBLE LITHOLOGY

Two samples collected in the New Pit West have similar lithologies to Facies 6 and 8 which underlie it. Figure A 3.1 shows the plot of the pebble lithology indices for Facies 6 through 9 of the New Pit Section. It shows that the values in Facies 9 are only slightly higher than the pebble lithology indices of Facies 6 and 8 (Fig. A3.1).

Plate 4.20 Silt laminae and diamictons of Facies 9 in the Main Section
deformed beneath a large clast and then rotated into their
present position. Compare these deformations to those in Plate
4.26 page 143. (knife handle is 9 cm).

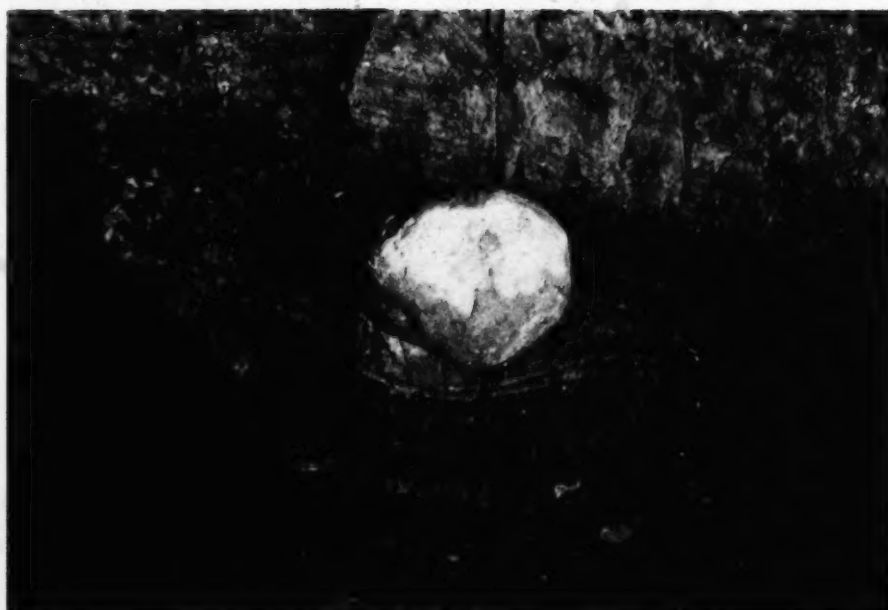


Plate 4.21 Facies 9 located at the river level in the Kettle Section, approx. 8 m below its location in the contiguous Main Section. The horizontal nature of the diamictons and silt laminae are preserved without disruption despite the 8m vertical displacement.



SUMMARY OF THE SEDIMENTARY FEATURES OF FACIES 9

The dominant features of facies 9 are its uniformly thick polymodal diamictons with silt laminae separating individual diamicton layers. The silt laminae are loaded and deformed by the overlying diamicton and often are incorporated as intraclasts into the bottom of the overlying diamicton. Outsized clasts deform the strata below them, interrupt the silt laminae, and are draped by diamicton and silt laminae layers. No lee-side shadows and scours are observed in association with the clasts. The four types of soft sediment clasts observed in facies 8 are also contained in Facies 9, with an increase in the proportion of laminated silt and clay intraclasts.

INTERPRETATION OF FACIES 9

The sedimentary features of Facies 9 are very similar to those of Facies 8 because of this the lodgement, meltout and subaerial stagnation environments will not be discussed as the arguments used for Facies 8 are equally applicable to Facies 9. A subaqueous environment of deposition is favored by the presence of the diamicton pellets, the laminated silt and clay clasts, pebble-cored mudclasts and clay balls are indicative of waterlain diamictons. The diamictons of facies 9 are interpreted as being deposited by subaquatic sediment flows because of their homogeneous texture, sharp internal contacts, uniform thickness, lateral continuity, and the inclusion of intraclasts and the loading of the silt laminae by the overlying diamictons. Symmetrical and asymmetrical drapes are the product of thin fluid sediment flows which cover the clasts as described in the discussion of the deposition of Facies 8. The shallow nature of the lake precludes rain-out from a slightly floating ice sheet. The silt laminae were most likely deposited by density currents as bottom currents cannot selectively deposit silts while winnowing away the clays and sands. The silt laminae may also be deposited by pelagic sedimentation through the water column. Silt laminae similar to those observed in Facies 9 have been interpreted as turbidite deposits in distal delta front to intermediate lake basin positions (Ashley, 1975, Banerajee, 1973, Gustavson, 1975). The large clasts which commonly occur above the silt laminae at the top of the diamicton layers and which deform the underlying strata are interpreted as dropstones for the same reasons as given for similar clasts in Facies 8.

The cause of the dipping of the strata as observed in the Main Section will be discussed at the end of this chapter.

FACIES 10, THE INTERBEDDED DIAMICTON AND SILT LAYER FACIES

FIELD CHARACTERISTICS

GENERAL APPEARANCE

This facies is composed of thin bedded diamictons which are interbedded with silt layers of four types. Exposures of Facies 10 range from 1.9 to 2.7 m in thickness. This facies has gradational upper and lower contacts with Facies 9 and 12 which respectively underlie and overlie it. The base of Facies 10 was defined as the bottom of the first silt layer greater than 3 cm in thickness above the uppermost diamicton bed of the underlying Facies 9. The diamicton beds and the silt layers can be considered as subfacies of Facies 10.

THE SILT LAYER SUBFACIES

The silt layers range from 3 to 18 cm in thickness. Individual layers maintain an approximately constant thickness for the tens of meters where they are best exposed, the Old Pit section. Small scale normal faulting is also prevalent in the silt layers as well as in the diamictons. There are four distinct types of silt strata:

1. graded silt laminae,
2. small scale ripple drift cross-lamination,
3. graded couplets of silt and clay.
4. massive silts.

An individual silt layer may be composed of one or more of these varieties but silt layers usually consist of a lower massive silt layer which grades into a graded silt laminae upper layer. The cross-laminated and silt-clay couplet varieties are relatively uncommon.

Massive silt layers commonly occur between the upper surface of the diamicton beds and the overlying stratified silts. This appears to be a transition zone between the silt layers and the underlying diamicton bed (Plate 4.24, 4.25) and contains a high proportion of irregularly shaped diamicton intraclasts. The volume of intraclasts may reach 25 % in the massive silts and the other silt bed types in direct

contact with the underlying diamicton interbeds. These intraclasts have the same appearance as the diamicton clots observed in the graded silt laminae and in Facies 6, 8, and 9. Outsized clasts (1-2 cm²) are also scattered throughout these layers.

Graded silt laminae (Plate 4.22, 4.23, 4.24, 4.25, 4.26) are from 0.1 to 10 mm in thickness and form packages of graded laminae up to 18 cm in thickness. Individual lamina have sharp basal contacts and show normal grading from very fine sand to very fine silt (Plate 4.25, 4.26). A thin clay layer a fraction of a millimeter thick may be present above the graded silt of the laminae (Plate 4.26). Diamicton pellets and outsized clasts observed within the graded silt laminae (Plates 4.25, 4.26) deform the laminae and are draped by them. Deformation structures closely mirroring the shape of the diamicton pellets and the outsized clasts are observed beneath these clasts. Subsequent silt laminae symmetrically drape these clasts. The initial drapes are steep-sided with the amplitude of each successive drape decreasing until the laminae regain their horizontal attitude (Plate 4.26). This silt layer type is most common at the base of the exposures.

The ripple drift cross laminations have 0.3 to 0.6 cm amplitudes and 1 to 3 cm wavelengths. The lee sides of the ripples are covered by platy minerals and coal fragments. Silt layers composed solely of cross-laminated silts range vary 1 to 4 cm in thickness.

Silt and clay couplets have basal graded silt layers with a gradational contact between the silt and clay components. Couplets are usually < .5 cm in thickness. The clay part of the couplet is thinner than the silt component. Sharp contacts are observed between the clay tops and silt bases of adjacent couplets.

THE DIAMICTON SUBFACIES

The diamicton beds are thin (4 to 14 cm), horizontally lying, with their bases and tops irregular on a centimeter scale. They maintain a relatively uniform thickness, and are conformably interbedded with the silt layers. Their appearance has three forms:

1. massive polymodal diamicton beds containing scattered laminated silt and clay intraclasts, and diamicton pellets,
2. diamicton beds which are composed entirely of agglomerated intraclasts,

Plate 4.22 Silty diamicton (1) of Facies 10 overlain by a massive silt layer (2) and by couplets of silt and clay (3). Note the shardy, pebbly texture of the diamicton (1). The diamicton is composed of diamicton pellets and intraclasts of clay and silt encased in a silty matrix. (knife handle is 9 cm).



Plate 4.23

Diamicton (1) composed predominantly of intraclasts of laminated silt and clay overlain by a massive silt layer (2) in which numerous diamicton clots are visible. Above the massive silt layer are thin graded silts (3) which also contain diamicton clots. The overlying diamicton (4) is also composed predominantly of intraclasts of silt and clay. (knife handle is 9 cm).



Plate 4.24 Pebbly-textured diamicton which has disrupted the graded silt
laminae (knife handle is 9 cm).

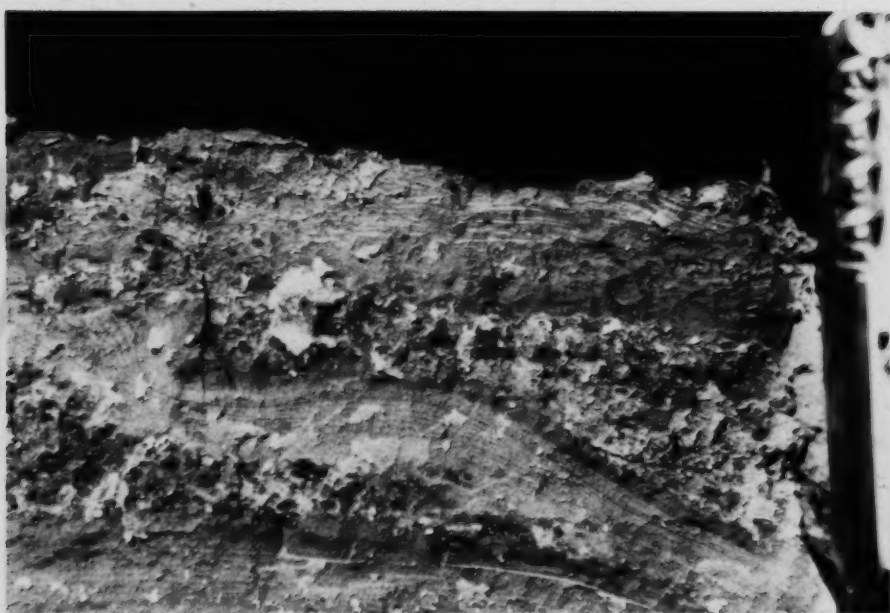


Plate 4.25 Graded silt layers of Facies 10 in the New Pit North containing numerous diamicton clots which are draped by successive silt laminae (knife handle is 10 cm).

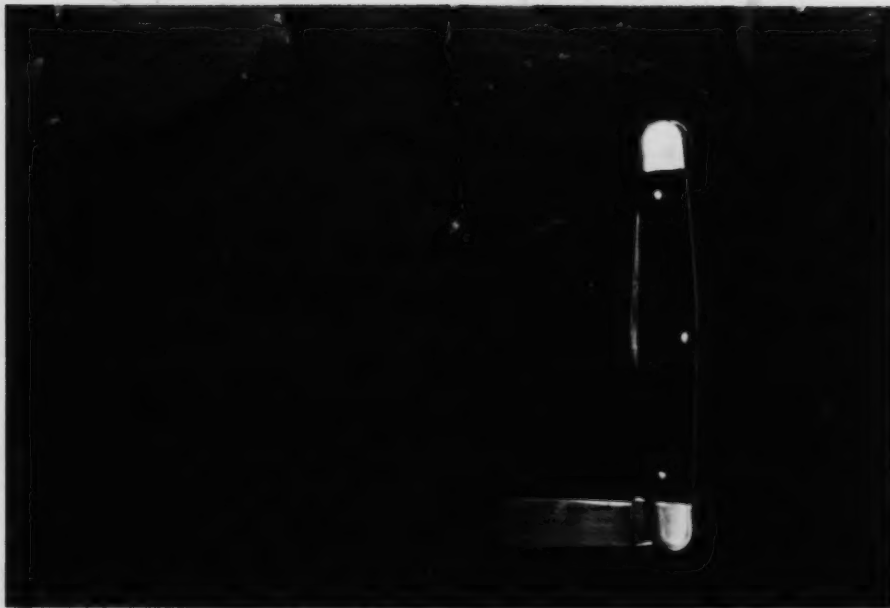


Plate 4.26 Graded laminae of Facies 10 in the New Pit North which are deformed beneath a dropstone and are steeply draped by successive laminae with the amplitude of the drape decreasing upwards. Note the similarity to the deformations beneath and drapes over large clasts observed in Facies 8 and 9 (pencil top for scale).



3. diamicton beds composed of intraclasts dispersed in a silty matrix (Plate 4.23).

Pebbles in all cases make up only 3 to 4 % of the diamicton.

The contacts between silt layers and the diamicton beds are distinct. The silt layers in close contact with the overlying diamicton layer are often loaded, splayed, broken and injected by the overlying diamicton layer (Plate 4.24). Occasionally intraclasts originating from the silt layer are incorporated into the base of the overlying diamicton.

DEFORMATION IN THE FACIES

In the Main section, Facies 10 has the same attitude as the underlying Facies 8 and 9 (Plate 4.31a,b). In the New Pit North section most of this facies is missing. An exposure (<0.75 m) composed of a thick layer of graded laminae and a diamicton layer, is truncated by a striated shear plane.

LABORATORY ANALYSIS

TEXTURAL ANALYSIS

The diamicton beds of this facies were not analysed due to the high proportion of intraclasts, which as they could not be removed would disaggregate during preparation for textural analysis resulting in inaccurate textural data. Textural analysis of four samples of the silt layers was performed. The silt layers texturally classify as a clayey silt (Shepard, 1954). The grain size parameters indicate that the silt layers are fairly well sorted and positively skewed.

THIN SECTIONS

Difficulties in impregnation hampered making thin sections from this facies. A single poor quality thin section was obtained of the graded silt laminae silt layer type. Features observed were, the sharp basal contacts of the laminae, grading within laminae, thin clay tops, and small scale normal faults with 1 to 2mm displacements.

SUMMARY OF FACIES 10

Facies 10 consists of layers of ripple bedded or graded silt laminae and rare occurrences of silt/clay couplets interbedded with thin horizontal diamicton beds. The

diamicton beds can have high percentages of intraclasts (up to 75%). In these instances the diamicton beds have an agglomerated pebbly texture. When the volume of intraclasts is less they are suspended in a silt clay matrix. The silt layers between the diamictons vary from 2 to 10 cm in thickness and are loaded, deformed and injected by the overlying diamicton bed. In many instances a transitional zone containing abundant rip-up clasts was evident between the diamicton bed and the overlying silt layer (Plate 4.23, 4.24). The silts of the transitional zone are either massive or contain disrupted silt laminae of various types. They infill the irregular upper surfaces of the diamicton beds. When the surface irregularities are infilled undisrupted silt laminae are deposited. Large clasts deform and pierce the bedding of the silt layers and are draped by the overlying silt layers. Intraclasts composed of blocks (1-2 cm) of the silt layers are incorporated into the base of the diamictons.

INTERPRETATION OF THE SEDIMENTARY FEATURES OF FACIES 10

Graded and rippled silt layers and rhythmic couplets described by Harrison (1975), Ashley (1975), and Banerjee (1973), have been interpreted as deposits of turbidity currents within glacial lakes. The large clasts which pierce the bedding and which are draped by the overlying silt layers fit the descriptions of dropstones (Harlan *et al.*, 1976; Banerjee, 1973; Jackson, 1969; Binda and van Eden, 1972; Young, 1970; Gravenor, 1980). The multiple graded silt layers with sharp contacts probably represent a distal delta environment to an intermediate lake position (Agterberg and Banerjee, 1973; Ashley, 1975). The couplets of silt and clay are seen in the intermediate to distal lake positions (Ashley, 1975). The diamicton pellets are similar to those described by Agterberg and Banerjee (1973) and Ashley (1975), who interpreted them as having been eroded from the underlying strata by turbidity currents, introduced by ice rafting, or emplaced by thin fluid debris flows.

The diamictons maintain a relatively uniform thickness throughout the exposure and are often composed of non-durable clasts. They load, disrupt, and deform the silt layers below them, incorporating blocks of the silt laminae into their base, features commonly associated with sediment flows (May, 1977; Evenson *et al.*, 1977). The survival of large numbers of nondurable clasts indicates that the sediment flow has not moved a great

distance from its point of initiation (Smith, 1972). These debris flows were emplaced in a subaqueous environment, as indicated by the intimate interbedding with the silt layers of turbidite origin.

DEPOSITION OF FACIES 10

The features of facies 10 do not match those expected in meltout tills, lodgement tills, or assemblages of subaerial debris flows. The glaciolacustrine processes represented by facies 10 are distal delta to intermediate lake turbidites, subaquatic sediment flows, and ice rafting. The rippled silt layers represent deposition by traction currents at the base of turbidity currents. The graded layers are deposited by traction currents, or from suspension from the turbidity current head. A position near the inflow is indicated by the character of the silt layers. Turbidite sedimentation is periodically interrupted by sediment flows which load deform and rip up clasts of the underlying silt layers. The irregular upper surface of the diamicton disrupts the normal pattern of the sedimentation of the turbidity currents causing a massive silt layer to be deposited. The currents erode clasts from the upper surface of the diamicton, transport them, and eventually deposit them in the transitional silt zone. When the irregular upper surfaces of the diamictons are infilled, the turbidity currents resume normal sedimentation depositing undisturbed rippled or graded silt laminae. Covering the diamicton surface also reduces the supply of diamicton pellets to the turbidity currents. Episodic deposition by sediment flows interrupts the deposition of rhythmites forming a deposit composed of interbedded diamictons and silt layers. Sporadic iceberg sedimentation introduces dropstones which deform and pierce the bedding beneath them and are draped by silt and diamicton layers.

FACIES 11, DEFORMED AND DISRUPTED SANDY AND SILTY DIAMICTON WITH CHAOTICALLY ORIENTED BLOCKS OF STRATIFIED SEDIMENT

FIELD DESCRIPTION

GENERAL FEATURES

This facies, seen only in the New Pit North section, is highly deformed and consists of blocks of diamicton and sorted sediments which are chaotically distributed within the section. The basal contact of Facies 11 is a shear plane which truncates Facies 8, 9 and 10

which underlie Facies 11 (Plate 4.27a,b). The contact is striated, unconformable, and of an irregular nature as shown in Figure A 1.1 in Appendix 1. Deformations, such as drag folds are associated with the shear plane (Plate 4.13).

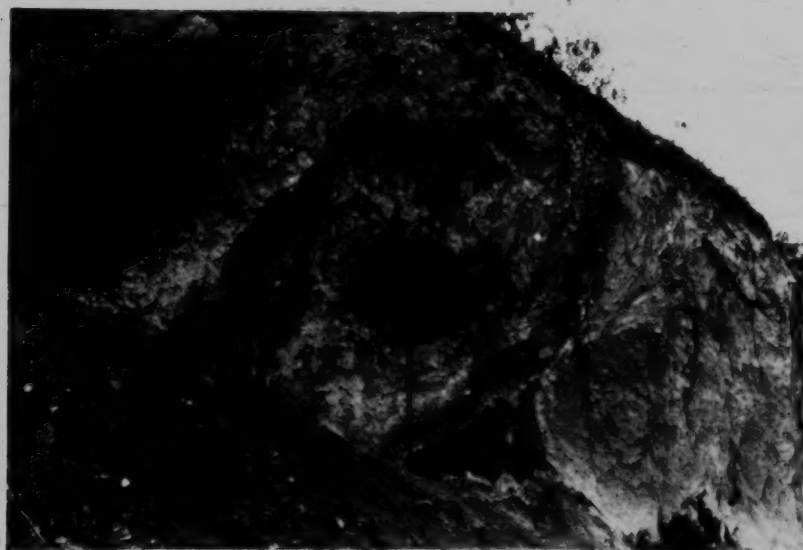
The facies itself is a "melange" of chaotically oriented blocks of stratified silts and sands with a diamicton-like matrix surrounding the blocks. The blocks vary in attitude from slightly dipping to overturned. No regular pattern of disruption was observed. In the west part of the section tabular blocks of stratified sediment are rolled over each other (Plate 4.29) and plunge to the northwest at angles from 30 to 50 degrees while the fold axes plunge to the north west at about 30 degrees.

INTERPRETATION OF FACIES 11

This facies represents slump disruption similar to that described by Crowell, (1957); Miller, (1963); McKee *et al.*, (1963a,b); Middleton and Hampton (1976); and Cook *et al.*, 1982. The formation of recumbent folds by movement of the overlying strata described by McKee *et al.*, (1963a, b) matches that observed in Facies 8 where it underlies Facies 11 (Plates 4.27a,b). Crowell (1957) described the formation of similar overfolded strata caused by slumping and discussed the difficulties of separating deposits formed by slumping from those deposited by ice sheets. Miller (1963) describes similar folded strata within the glaciolacustrine sediments of the Coppermine River in Alaska. Presence of the blocks and slabs in the diamicton matrix indicates that the material which slumped was a mixture of consolidated and semiconsolidated sediments. The deformation of the sediments probably coincided with the incision of the Battle River valley after glaciation as the slump structures are approximately perpendicular to the Northwest trending valley walls. It is unlikely that the deformation was induced by glacial override as the drag folds at the edge of the unit indicate a downward movement of the material, not an upward shearing as expected from over-riding. The *en-echelon* folds also indicate drag folding to the east and northeast conforming to the valley slope and indicating movement down the valley sides and not to the south and southwest as would be expected if they were produced by glacial override. The only multiple beds distinguishable in the western part of the New Pit North section dip away from the direction of ice movement in the area.

Plate 4.27a, (top of the page) Plate showing the shear plane (1), and dragfolds associated with it. The chevron folds of Plate 4.13 (2) were formed by movement along this shear plane.

Plate 4.27b, (bottom of page) Rolled layers of silt and sand observed in Facies 11 of the New Pit North (ice pick is approx. 80 cm). The pick is approximately 80cm.



B

FACIES 12, GRADED SILT BEDS COMPOSED OF GRADED SILT LAMINAE WITH MINOR CLAY INTERBEDS

FIELD DESCRIPTION

GENERAL FEATURES

This facies was only observed in the West Pit section. It consists of silt layers composed of graded silt laminae with thin interbeds of massive-appearing clay. Facies 12 unconformably overlies the sands and gravels deposited by the pre-glacial Red Deer River. This unconformable contact is planar and sharp and can be traced for 85 meters (Plate 4.28). The contact between Facies 12 and the overlying Facies 13 is planar, gradational, and continuous for the 85 meters it was exposed. The silt beds range from 10 to 20 cm in thickness and are traceable over the entire 85 meter exposure. The beds are composed of graded silt laminae 1 to 15 cm in thickness, which have sharp planar contacts between each other. The laminae have normal grading which ranges from very fine sand to very fine silt. The laminae are thickest at the base of the exposure and progressively thin upwards through the section.

The clay interbeds mark the breaks between silt beds. The clay beds are massive-appearing with gradational lower contacts with the silt laminae below them and sharp contacts with the overlying silt laminae. The clay beds are approximately 1 to 4 cm in thickness. The clay beds appear at .85, 1.19, 1.49, 1.74, 2.02, 2.23, 2.46, 2.63 meters above the contact with the preglacial gravels, showing a general decrease in thickness of silt beds between successive clay beds.

INTERPRETATION OF FACIES 12

The graded silt laminae which compose the bulk of this facies unconformably overlie pre-glacial sands and gravels along a planar contact, which was probably formed by glacial erosion. This contact is a relict feature and not formed by the mechanisms which deposited the silts of Facies 12. The graded nature of the silts, the sharp planar contacts within the unit, and their repetitive nature indicate that they are the product of density currents flowing into a lake. The predominance of silt and graded beds indicate that these deposits were probably deposited in an intermediate lake position (Ashley, 1975). The clay layers would represent suspension deposits and may be related to suspension deposition

9

Plate 4.28 The Far West Pit Section, (number 14) showing the sharp planar contact (1) between the pre-glacial sand and gravel (2) and Facies 12 (3). Facies 13 (4) is located in the upper part of the section. (ice pick is approx. 80 cm).



of the winter clay member of glaciolacustrine rhythmites (Ashley, 1975). The initially greater thickness of the silt layers may indicate a nearby sediment source which as time passed, receded, causing the decreasing thickness of the silt layers between the clay band towards the top of the section or initially strong density current inflows which decreased in strength over time (Smith 1972).

FACIES-13, RHYTHMIC COUPLETS

FIELD DESCRIPTION

GENERAL FEATURES

The rhythmic couplet facies is poorly preserved in the study area as it occupies the uppermost part of the sections and is the most subject to subaerial erosion and soil formation processes which disrupt the sedimentary features of the facies. The facies is found in the center of the study area and in the western part of the study area. In the center of the study area it is underlain by Facies 10 while in the western part of the study area it is underlain by Facies 12. The contacts in both cases are gradational and conformable.

The facies is 0.25 to 0.6 m in thickness and composed of silt and clay couplets. These couplets are from 0.5 to 2 cm in thickness with the thicker couplets located at the base of the facies. The silt portion of the couplet is graded, thicker at the base of the facies than at the top, and forms a sharp contact with the clay portion of the laminae below it. The silt grades upwards into the clay portion of the couplet. The clay appears to be massive with no grading or visible sedimentary structures. The thickness of the clay member increases upwards in the facies. In the West Pit section the clay member is always thicker than the silt member. Outsized clasts from gravel to boulder in size which deform the couplets below them are observed sporadically throughout the facies. These clasts are draped by subsequently deposited couplets. In the case of extremely large clasts the rhythmic sedimentation pattern is disrupted in the vicinity of the clast but is maintained outside the area influenced by the clast.

In the Main section, the rhythmites of Facies 13 are deformed and folded and have approximately the same dip as the other facies which occur in the Main Section.

INTERPRETATION OF FACIES 13

The rhythmites of this facies are couplets of silt and clay. Initially at the base of the unit the silt part of the couplet is thicker than the clay part but as the top of the section is approached the clay member of the couplets becomes dominant. Ashley (1975), interprets rhythmites with thicker silt components to be deposited in a mid-lake location. The decrease in the silt layer thickness indicates either that the distance to the sediment source increased through time or the strength of the turbidity currents has decreased and only peak inflows or exceptionally strong currents were able to deposit in the center of the lake (Ashley, 1975). Between turbidite inflows suspension sedimentation forms the thick clay layers (Ashley, 1975). Therefore deposits such as these represent either sediment starvation of the lake or locations far removed from inflowing rivers (Ashley, 1975). Large clasts which deform bedding in such manners have been interpreted as dropstones (Crowell, 1957; Agterberg and Banerjee, 1973; Young, 1970; Binda and van Eden, 1972; Gravenor, 1980). The association of dropstones and rhythmites is common in glaciolacustrine settings.

C. DIAGENESIS OF THE SEDIMENTS IN THE STUDY AREA

The upper parts of all sections visited were observed to be yellow-brown in color. Below this upper yellow-brown layer the deposits were gray-black. The depth of the yellow discoloration varied from section to section and the boundary between the yellow-brown layer and the gray-black layer was either a sharp, linear boundary that was horizontal or inclined, or the boundary was gradational over 10's of cm. Where the boundary was sharp, silt and clay layers were observed to occur along the contact. Where gradational boundaries were observed there was no discernable clay layer or other bedding feature between the two layers. Thick sand beds and lenses also occurred at the break between the units. Where a clay layer present at the boundary between the yellowbrown and gray-black layers was broken by a joint or fracture the yellow-brown discoloration followed along the break discoloring a zone around the break. In several cases where a gradational contact was present the boundary of the yellow-brown layer passed through several facies types. For example in the Main Section the boundary passed through Facies 8, 9, and 10. The upper yellow-brown layer is usually over-consolidated and

very compact with well-developed columnar joints. Sedimentary features such as graded laminae, clay clasts, and thin diamicton layers which are readily visible in the lower gray-black zone are destroyed in the upper yellow-brown zone. This can be best explained by reference to Facies 10 in the Main Section. In the Main Section Facies 10 is inclined and can be traced upwards from the gray-black lower layer into the yellow-brown upper layer. In the lower gray-black layer the sedimentary features of Facies 10, such as the intraclasts in the diamicton layers, the cross-laminated ripples and graded silt laminae are readily observed (Plate 4.29a). When individual diamicton and silt layers are traced upwards into the discolored layer their sedimentary features are destroyed. Plate 4.29b shows several diamicton and silt layers of Facies 10 which were traced into the upper unit. No sedimentary features are discernible even in thin section.

INTERPRETATION AND DISCUSSION

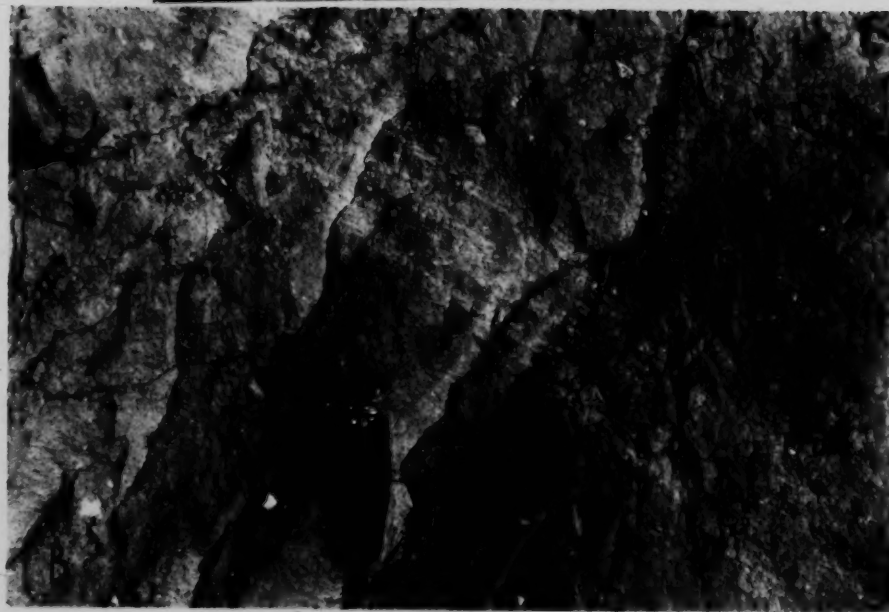
The upper discolored layer is a weathered zone in which the sulfur minerals derived by glacial erosion from the bedrock have been oxidized (Eyles and Sladen, 1982; Hendry, 1985). The deep weathering probably occurred during the Hypsithermal when the watertable dropped in response to the increased aridity of the climate (Hendry, 1985). Capillary pressures exerted on the sediment upon dessication can exert forces sufficiently strong to cause overconsolidation of the same degree as caused by ice sheet loading (Soderman and Kim, 1970; Quigley, 1975). The high capillary pressures also cause the formation of paired near-vertical joints (McGown *et al.*, 1974; Quigley, 1975). Another effect of the high capillary pressures is the destruction of the sedimentary structures contained in the facies of the desiccated upper layer. The diamictons and silt layers are now structureless making correct interpretation of their origin impossible.

Oxidation which accompanies the watertable drop causes the color differences between the two subfacies of Facies 10, to be reduced to slight variations between two tones of yellow. This makes differentiation of the two subfacies of facies 10 on the basis of color impossible.

The degree of alteration of the sediments by deep-weathering and consolidation effects due to a drop in watertable will greatly affect the quantity and the quality of the observations which can be made on individual units and thereby the conclusions drawn

Plate 4.29a. (top of the page) The dipping diamicton and silt beds of Facies 10 in the Main Section are easily distinguishable in this photograph as well as smaller sedimentary features of the facies.

Plate 4.29b. (bottom of the page). This photograph shows exactly the same beds as 4.29a after they have been traced upwards into the oxidized part of the Main Section. The beds of silt laminae appear as streaks of a slightly lighter color while the diamicton appears to be massive with no sedimentary features. This pair of photographs shows the dramatic effect that post-depositional changes can have on glacial diamictons and the materials interbedded with them. (knife handle is 9 cm).



from the data. Destruction of sedimentary structures by groundwater table shifts may have an important effect on the interpretation of a diamicton. The silt layer subfacies of facies 10 was altered from distinct graded silt laminae to streaks and wisps of silt whose turbidite origin is no longer identifiable. They may be mistaken for silt streaks which form by shearing during the lodgement process (Boulton, 1976a; Dreimanis, 1982) causing the diamicton to be incorrectly identified as a lodgement till. This problem is especially acute where the diamicton is indurated thereby making the measurement of macrofabrics impossible. Sedimentary features of the diamicton may also be affected by weathering and collapse of the sediment structure as in the Facies 10 where the diamicton clots and intraclasts are no longer distinguishable. Since identification of these features is important to the interpretation of glaciolacustrine diamictons their removal may render the diamicton unidentifiable. The conclusion of all this is that one should not try to interpret diamictons which have been greatly affected by dewatering and diagenesis.

V. DISTRIBUTION OF FACIES AND THEIR ASSOCIATIONS IN THE STUDY AREA

A. INTRODUCTION

In Chapter 4 thirteen facies were presented and interpreted individually. Interpretation of facies in isolation does not take into consideration the vertical associations between facies or their distribution within the study area. The context in which facies occur is very important for:

The key to interpretation is to analyse all the facies communally in context.

The sequence in which they occur thus contributes as much information as the facies themselves. (Walker, 1984, p 2)

This chapter will discuss the vertical and lateral associations observed among the facies to further support the interpretations made in Chapter 4, summarize the depositional environments of the facies, and develop a general depositional model for diamictos deposited from ice grounded in ice-proximal lakes.

B. FACIES ASSOCIATIONS

For ease of reference, Table 4.1 listing the sections in the study area and the facies which they contain, is repeated in this chapter (Table 5.1). In this table three main facies associations can be seen:

4. the well-sorted, stratified sediment-diamicton association which consists of three sequences; Facies 2, 5; Facies 3, 5; and Facies 4, 5.
5. the diamicton-rhythmic couplet association consisting of three slightly different vertical sequences; Facies 6, 8, 9, 10, and 13; Facies 7, 8, 9, 10, and 13; and Facies 6, 8, 9, 10, and 11.
6. the graded silt bed-rhythmic couplet association of Facies 12 and 13.

THE WELL-SORTED STRATIFIED SEDIMENT-DIAMICTON ASSOCIATIONS

The sequences in this association all involve transitions from well-sorted stratified sediments, interpreted as glaciofluvial deposits, to an overlying diamicton which has been interpreted as glaciolacustrine diamicton. These transitions have been schematically shown in Fig 5.1a-d. The transition from Facies 2 and Facies 4 to Facies 5 is gradual as shown by

Table 5.1 SECTIONS STUDIED AND THE FACIES WHICH THEY CONTAIN

Section	Facies	Present				
Highway 13 Roadcuts	4	5				
Delta Pit Site	3	5				
Ridge Section 1	3	5				
Ridge Section 2	3	5				
Hummocky Sand Pit	2	5				
Riverbend 1	6	8	9	10		
Riverbend 2	7	8	9	10	13	
Main Section	7	8	9	10	13	
Kettle Section	7	9	7			
New Pit South	6	8	9	10	13	
New Pit West	6	8	9	10	13	
New Pit North	6	8	9	10	11	
Old Pit	(2)	6	8	9	10	13
Far Bridge Section	7	8	9?	10	?	
West Pit Section	12	13				

Figure 5.1 a-d, Schematic diagrams of the Facies Associations between
well-sorted sediments and overlying diamictons.

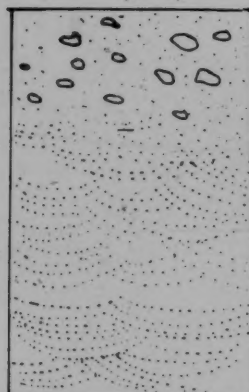
5.1a - Facies 2 - Facies 5 Association

5.1b - Facies 3 - Facies 8 Association

5.1c - Facies 3 - Facies 5 Association

5.1d - Facies 4 - Facies 5 Association

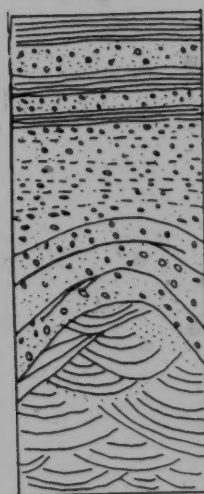
5.1A



FACIES 5

FACIES 2

5.1B



FACIES 13

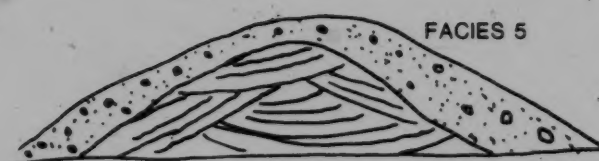
FACIES 10

FACIES 9

FACIES 8

FACIES 3

5.1C



FACIES 5

FACIES 3

5.1D



FACIES 5

FACIES 4

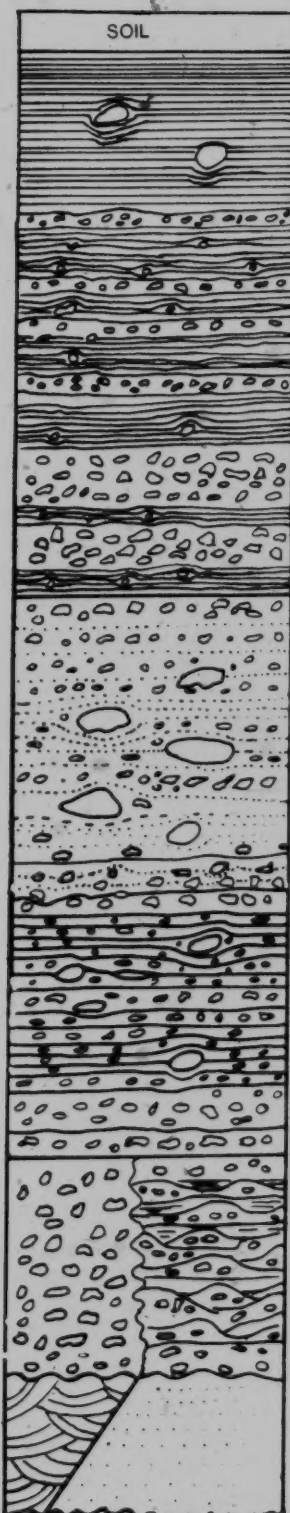
the gradational contact indicating inundation of the glaciofluvial environment by a lake. The transition of Facies 3 to Facies 5 is sharp and unconformable, probably indicating that the esker was surrounded by ice which when melted, caused the esker to be draped unconformably by diamicton. The transition from Facies 3 to the main part of the diamicton-rhythmic couplet association (Facies 8, 9, 10, 13) is also sharp. Units within facies 8 are draped over facies 3 (Plate 4.3, Fig. 5.1b). This draping relationship and the sharp contact is similar to those hypothesized between sub-aqueous eskers and the overlying lake deposits (Gustavson, 1975).

THE DIAMICTON-RHYTHMIC COUPLET ASSOCIATION

The diamicton-rhythmic couplet association can be divided into three slightly different sequences. The most common sequence consists of Facies 6, 8, 9, 10, 13; of which four complete sequences exist. The next most common sequence is 7, 8, 9, 10, 13; of which two complete sequences exist. The sequence 6, 8, 9, 10, 11; is observed only once. In addition to these full sequences, several incomplete sequences are observable (Table 5.1). The contacts between all facies are gradational except for the transition between Facies 10 and 11 in which the contact is marked by a striated shear plane which abruptly truncates facies 10. Facies 11 has already been interpreted as a mass movement deposit which was formed when the valley walls of the Battle river slumped in response to incision of the river valley. This event accounts for the sharp break between Facies 10 and 11. Regardless of which sequence is studied the core of the sequence remains the same with transitions from Facies 8 to 9, 9 to 10, and 10 to 13. The replacement of Facies 6 by Facies 7 will be explained in the discussion of the deposition of the facies. These sequences are schematically shown in Fig. 5.2.

When the different sequences are combined a general sequence beginning with either Facies 6 or 7 and then passing in turn, through Facies 8, 9, 10, and 13 can be made (Figure 5.2). In every instance the transition between facies are gradational, indicating that there was no major break in sedimentation between them (Walker, 1984). A further indication that there was no break in sedimentation is illustrated by the pebble lithology data (Table A3.1, Table A3.2, Figure A3.1). The pebble lithology indices remain constant through the sequence indicating that the sequence is complete and contains no hidden

Figure 5.2. Composite diagram of the Diamicton-Glaciolacustrine Facies Sequence (Facies 6, 8, 9, 10, and 13 or Facies 7, 8, 9, 10, and 13).



Facies 13

Rhythmic Couplets and Graded Silt Laminae — graded silt layers ≤ 2 mm in thickness, couplets of silt and clay 5 mm to 1 cm, presence of numerous dropstones deforming laminae and couplets below them, gradational contact with underlying Facies 10

Facies 10

Interbedded Diamictons and Silt Layers — horizontal diamicton layers, 2-17 cm in thickness, pebbly-textured, abundance of intraclasts (up to 80%), many silt and clay intraclasts present in the diamictons, diamicton layers have irregular contacts with the silt layers above and below them; silt layers composed predominantly of graded silt laminae 1-10 mm in thickness, rare couplets of silt and clay, and rare microscale ripples. Silt layers deformed by the overlying diamicton layers, massive silts usually occur between the diamicton tops and the bedded silt layers, gradational contacts with overlying and underlying facies

Facies 9

Diamictons intercalated with silt laminae — consists of diamicton layers, silt laminae, and dropstones; has gradational contacts with overlying and underlying facies. Diamictons: horizontal layers, 2-20 cm in thickness, polymodal, homogeneous texture, siltier than Facies 8, contain laminated silt and clay intraclasts, clay clasts, diamicton pellets, and pebble-cored mud clasts, silt laminae 1-3 mm thick, loaded and deformed by overlying diamicton layer, minor occurrences of sand laminae. Dropstones occur singly or in clusters, predominantly horizontally oriented a-b axial planes, deformation of silt laminae and diamictons below the clast, abrupt termination of the silt layers at clasts and draping of the dropstones by overlying diamictons and silt laminae, clasts can occur singly or in clusters and have predominantly horizontal a-b axial planes

Facies 8

Diamictons intercalated with Sand Laminae — consists of diamicton layers, sand laminae, and dropstones; gradational contacts with underlying and overlying facies. Diamictons: horizontal layers 8 mm to 20 cm, contain diamicton pellets, laminated silt and clay clasts, clay intraclasts, and pebble-cored mud balls, polymodal, homogeneous textures, random fabrics, sand laminae: 1 grain to 2 mm usual thickness, usually structureless, rare planar beds in thicker laminae (> 2 mm), pebble lags beneath thicker (> 2 mm) sand laminae, continuous for 10's of meters before obscured by colluvium; dropstones: occur singly or in clusters, predominantly horizontal a-b axial planes, cause deformation of sand laminae and diamictons below them, cause abrupt terminations of sand laminae, and are draped by successive laminae and diamictons, lee-side shadows and scours observed on the west side of some of the large clasts

Facies 6

Unstratified Diamicton — 74 - 1.5 m thick, diamicton pellets and pebble cored clay balls, rare distorted silts, random fabrics, unconformable lower contact with the pre-glacial sands and gravels has an oxidized aureole (4-9 cm thick), diamicton appears to be loaded into the underlying sands and gravels. Upper contact with overlying Facies 8 is gradational

Facies 7

Lensoid shaped pebbly-textured diamictons — Facies consists of diamictons interlayered with the silt beds, gradational contact with overlying Facies 8. Diamictons: lenses 3-6 m in width and 10-60 cm in the thickest part of the lens, pebbly appearance. Silt beds: 10-25 cm thick, 2-3 meters in thickness in width, diamictons load and deform the silt layers, numerous recumbent folds observed in the diamictons where they are in contact with the silt layers

Pre-glacial sands and gravels/Bedrock

Pre-glacial sands and gravels and bedrock — pre-glacial sands and gravels are quartzites and mountain-derived carbonates, bedrock is of the Horseshoe Canyon Formation

depositional breaks. The gradational boundaries between the facies implies that the facies vertically adjacent to each other were once laterally adjacent (Walker, 1984). This fact will become important when the depositional model is discussed.

The gradational contacts between facies also strengthens the interpretation that the massive diamicton units originated subaquatically. Facies 8, 9, and 10 are readily interpreted as subaquatic diamictons on the basis of the interbeds which they contain. The interpretation of Facies 6 as a subaquatic diamicton is strengthened by its gradational contacts with Facies 8.

THE GRADED SILT BEDS-RHYTHMIC COUPLET ASSOCIATION

The final sequence to be described is the graded silt bed-rhythmic couplet association which consists of Facies 12 and 13 (Fig. 5.3). Facies 12 consists of silt beds interlayered with clay bands. The silts have been interpreted as the deposits of turbidity underflows while the clay bands represent periods of quiet water sedimentation. Facies 13 consists of rhythmic couplets. The facies of this sequence represent sediments deposited in the central basin of a lake. These deposits may be the lateral equivalents of the sediment flow deposits of Facies 8, 9, or 10. Initiation of turbidity currents by sediment flows has been described by Morgenstern (1967), Hampton (1972), and Middleton and Hampton (1976). Ashley (1975) states that thick silt layers may represent the deposits of underflows initiated by mass movement events.

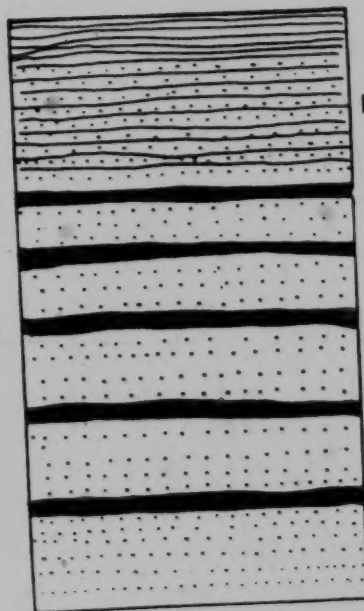
The gradual transition to more quiet water sedimentation as shown by the increasing frequency of clay bands upward in the section indicates a decrease in the strength of the turbidity currents which may relate to a movement of the ice front further away. The rhythmic couplets of Facies 13 indicate more distal rhythmite sedimentation as thick clay components of rhythmites are linked to distal deposition by turbid underflows. Occurrence of distal rhythmites over the proximal rhythmites of facies 12 indicates a retreat of the source area allowing the superimposition of these facies.

AREAL DISTRIBUTION OF THE FACIES WITHIN THE STUDY AREA

In the previous section the facies were dealt with in terms of their vertical associations. Three types of associations were observed. This section will consider the



Figure 5.3. Schematic diagram of the Graded Silt Bed - Rhythmic Couplet Association.



Facies 13
Rhythmic couplets

Facies 12
Graded silt laminae beds
and clay interbeds

areal distribution of the facies and discuss the lateral relationships between the facies.

Reading (1978) recognizes three stages of facies interpretation:

1. an initial working hypothesis,
2. a paleogeographical interpretation which shows the orientation and approximate location of environmental belts,
3. and the realistic interpretation when the exact location of the environmental belts is established.

The present study can only progress to the paleogeographical stage as the exact location of the boundaries between environments is not known due to the incomplete nature of the exposures.

Fig 1.2 shows the locations of the fourteen sections in the study area. When the facies sequences established in the beginning of this chapter are linked to the sections in which they occur and subsequently plotted on the study area map, four distinct environmental zones are observable:

1. The Glaciotectonic Zone containing Facies 1,
2. The Glaciofluvial Zone containing Facies 2, 3, 4, 5.
3. The Glaciolacustrine Diamicton Zone containing Facies 6, 7, 8, 9, 10, 11, 13.
4. and the Glaciolacustrine Zone containing Facies 12, 13.

According to Walther's Law only facies which are laterally contiguous can be vertically superimposed upon each other without breaks in sedimentation. When the lateral relationships between the four zones are considered it is observed that they represent an incomplete transition from the ice into the basin of an ice proximal lake. The fact that the lateral facies transitions are broadly similar to those observed in the vertical supports the interpretation of the vertical facies sequences which overall show a superimposition of distal sediments over more proximal sediments with time as the position of the grounding line of the ice receded to the east.

Sedimentation within the lake can be divided into two zones: the proximal, in which diamictons, glaciofluvial, ice rafted, bottom current, and turbidity current sediments are deposited; and the basinal, in which the sediments are primarily turbidite deposits with dropstones introduced by ice rafting.

The deposits in the basinal environment will vary according to their distance from the source of sediment inflow. Intermediate positions will have multiple graded beds, while the most distal positions will have rhythmites in which the clay member is much thicker than the silt member.

C. SURFICIAL GEOLOGY, EVOLUTION OF THE HUMMOCKY TERRAIN

In the previous section of this chapter the facies in the Diamicton-Glaciofluvial Sequence were interpreted on the basis of their total context and assemblage of sedimentary features to be subaquatic glacialigenic diamictons. This interpretation can be further strengthened by analysis of the surficial geology of the study area.

SURFICIAL GEOLOGY

Fig 5.4 shows the surficial geology and landforms of the study area. The map was constructed using the surficial geology map produced by Stalker (1960) supplemented by data collected for this thesis. The study area can be divided into flat plains and hummocky terrain. The surficial deposits of the plain area are lake sediments which can be further subdivided into outer sand and silt zone and an inner silt and clay zone (Fig 5.4). Facies 12 and 13 occur in the silt and clay zone of the study area. Facies 1, 2, 6, 7, 8, 9, 10, 11, and 13 are found in poorly developed to well-developed hummocky terrain. The hummocky terrain contains three different facies associations:

1. In the north, in the vicinity of Bittern Lake the irregular hillocks are composed of thrust and deformed bedrock slabs of Facies 1.
2. In the central part of the study area the hummocks are composed of the glacialigenic sediments of Facies 6, 7, 8, 9, 10, 11, and 13 which are located in Region 3.
3. In the south central part of the study area the hummocks are formed of faulted sands and gravels with rare diamicton interbeds of Facies 2 draped by Facies 5.

The hummocky terrain in the central and south central part of the study area has an narrow, arcuate shape (Fig. 5.4).

Figure 5.4. Map of the surficial geology of the study area.

A - A topographic profile of Figure 5.5a

B - B topographic profile of Figure 5.5b



1 - Well-developed hummocky terrain



2 - Hummocky terrain



3 - Flat to undulating terrain



4 - Silt and clay surficial deposits



5 - Sand and silt surficial deposits



6 - Pre-glacial gravels

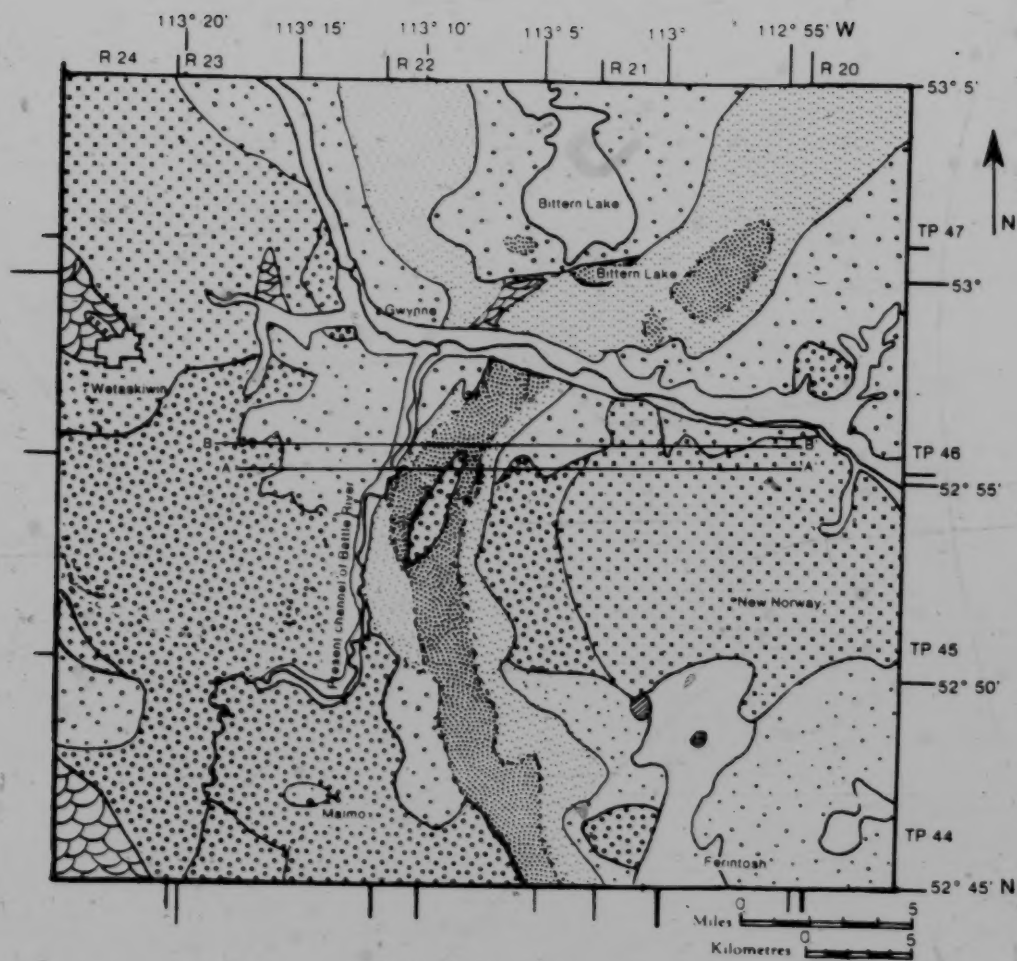


7 - Alluvium



8 - Dunes

after Stalker, 1960



EVOLUTION OF THE HUMMOCKY TERRAIN

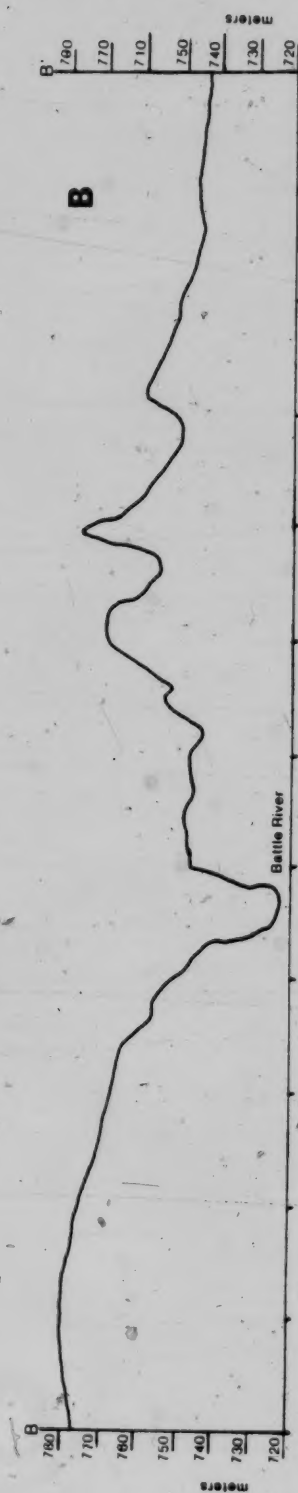
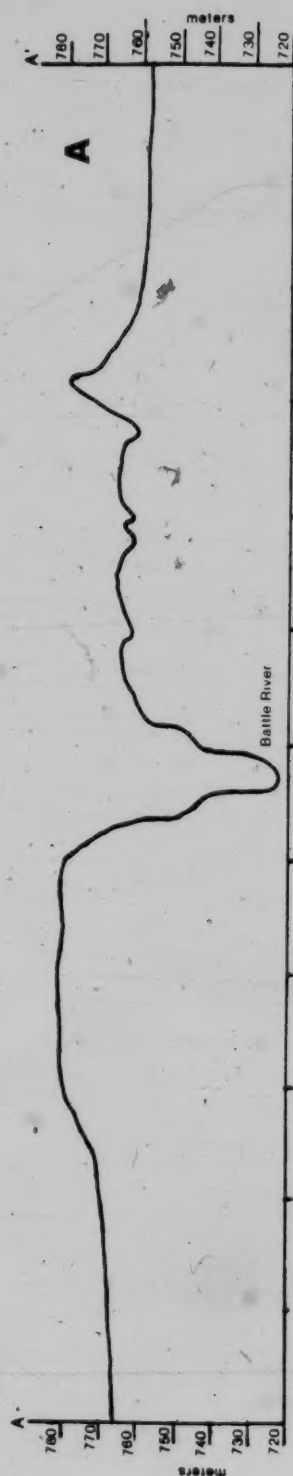
The hummocks of the three areas are not formed by the same mechanisms. The genesis of the hummocky terrain in the vicinity of Bittern Lake is easily related to the glaciotectionism which folded the bedrock. Hummocks in the sorted sands and gravels of the south central region area were formed when ice blocks, covered by the ice-proximal glaciofluvial sediments of Facies 2 and the glaciolacustrine diamicton of Facies 5, melted.

The hummocky terrain in the central part of the study area is atypical when compared to hummocky terrain formed subaerially. Hummocky terrain formed by subaerial wasting of large areas of stagnant ice is usually distributed over a wide area, the hummocks rise above the general elevation of the plain, and are formed by a process of multiple relief inversions in which the predominant sedimentary process is mass movement by debris flows (Gravenor and Kupsch 1957, Parisek, 1969). The hummocky terrain in the central part of the study area differs in that the zone of the hummocks is an arcuate band < 1 km in width (Fig. 5.4). The top of the arcuate band of hummocks is at the same general elevation as the plain on the west side of the Battle River with the majority of the hummock tops below this elevation (Fig. 5.5a, 5.5b). The bedrock geology shows a upward slope from the river level to the plain level forming a natural basin which has been partially infilled by the glacial sediments.

The Main and Riverbend 2 sections are exposures cut through two hummocks. These sections show that the stratigraphy of the hummocks near the river matches the Diamicton-Glaciolacustrine Sequence described in the New Pit and Old Pit sections which are formed in slightly rolling terrain. In the Main section the strata of Facies 8, 9, 10, and 13 are rotated up to 60 degrees from the horizontal. The facies observed in these sections are interpreted to have been deposited in a subaquatic environment which shows an upward sequence from massive diamicton to diamictons intercalated with sand and silt laminae to diamictons interbedded with turbidites culminating in glaciolacustrine rhythmites. Within the section, sedimentary features are preserved undisturbed (Plates 4.12, 4.21) even after dislocation and subsidence. The mirror images beneath the large clasts are rotated to the same degree as the strata indicating that the rotation post-dates the formation of the strata. Similarly the glaciolacustrine sediments of Facies 13 must have been originally deposited in a horizontal position and then rotated.

Figure 5.5a. Topographic profile along line A to A' on Figure 5.2, illustrating the narrow width of the hummocky terrain and its elevation which matches that of the plain level on the west side of the Battle River.

Figure 5.5b Topographic profile along line B to B' on Figure 5.2.



In the Kettle section which is contiguous with the Main section, (Plate 4.21), the strata of Facies 9 are present approximately 8 m below where they occur in the Main section, the section is bounded by high angle faults and the strata in the section are undisturbed. The preservation of Facies 9 at an elevation equal to that of Facies 7 indicates that the two Facies originated from the same glacial advance. Preservation of the stratigraphic sequences in the hummocks indicates that the hummocks were not formed by the relief inversion mechanism (Gravenor and Kupsch, 1963) but formed by slow lowering of the stratified deposits caused by the meltout of ice blocks contained within the sediment. The subsidence lowered the blocks without significantly disturbing the sedimentary features or the stratigraphic sequence in the glacial deposits. MacKenzie (1969) estimated that the meltout of buried ice beneath a thick sediment cover would be .66 mm a day for the ablation season. Lawson (1979) estimated a meltout rate of 6.3 mm a day. Preservation of ice beneath thick sediment covers for a sufficiently long period of time for the sediments to become stabilized is documented in observations of the drunken forest on part of the terminus of the Malaspina glacier in Alaska and the Klutan Glacier in the Yukon in both cases trees have become established on top of the ice-cored moraine which is now melting out (Driscoll, 1974, 1980, Watson, 1980). The low rate and volume of meltwater production allows the sediments to drain, permits consolidation of the deposits, and prevents relief inversion enabling the stratified deposits to be lowered without significant disruption of their sedimentary features or their stratigraphic sequence.

The correspondence of the elevation of the hummock tops with the general plain level also supports the hypothesis of gradual lowering by meltout of blocks from beneath a glaciolacustrine sedimentary sequence. Additionally hummocks formed in a subaerial stagnation environment are positive-relief features in that they stand higher than the plain level.

The narrow arcuate shape of the moraine can be explained with reference to a glaciolacustrine environment. Holdsworth (1973a,b) and Barnett and Holdsworth (1974) described the formation of subaquatic moraines by undermelting of the ice at the lake-ice interface. These subaquatic moraines would be the source of much of the sediment which would be redistributed by mass movement through the lake.

The preservation of the stratigraphic sequence in some of the hummocks, the narrow arcuate shape of the hummocky band, and the elevation of the hummock tops, support the interpretation already stated that the diamictos of the central part of the study area were formed in a glaciolacustrine setting.

D. DEPOSITION OF THE FACIES SEQUENCES WITHIN THE STUDY AREA

Interpretation of the total assemblage of glacial diamictos and other related sediments of the study area in the context of the lateral and vertical facies associations supports the original hypothesis that the diamictos originated in a glaciolacustrine setting through the interaction of several processes.

Figure 5.6 illustrates the processes which were active in forming the facies observed in the study area and diagrammatically accounts for:

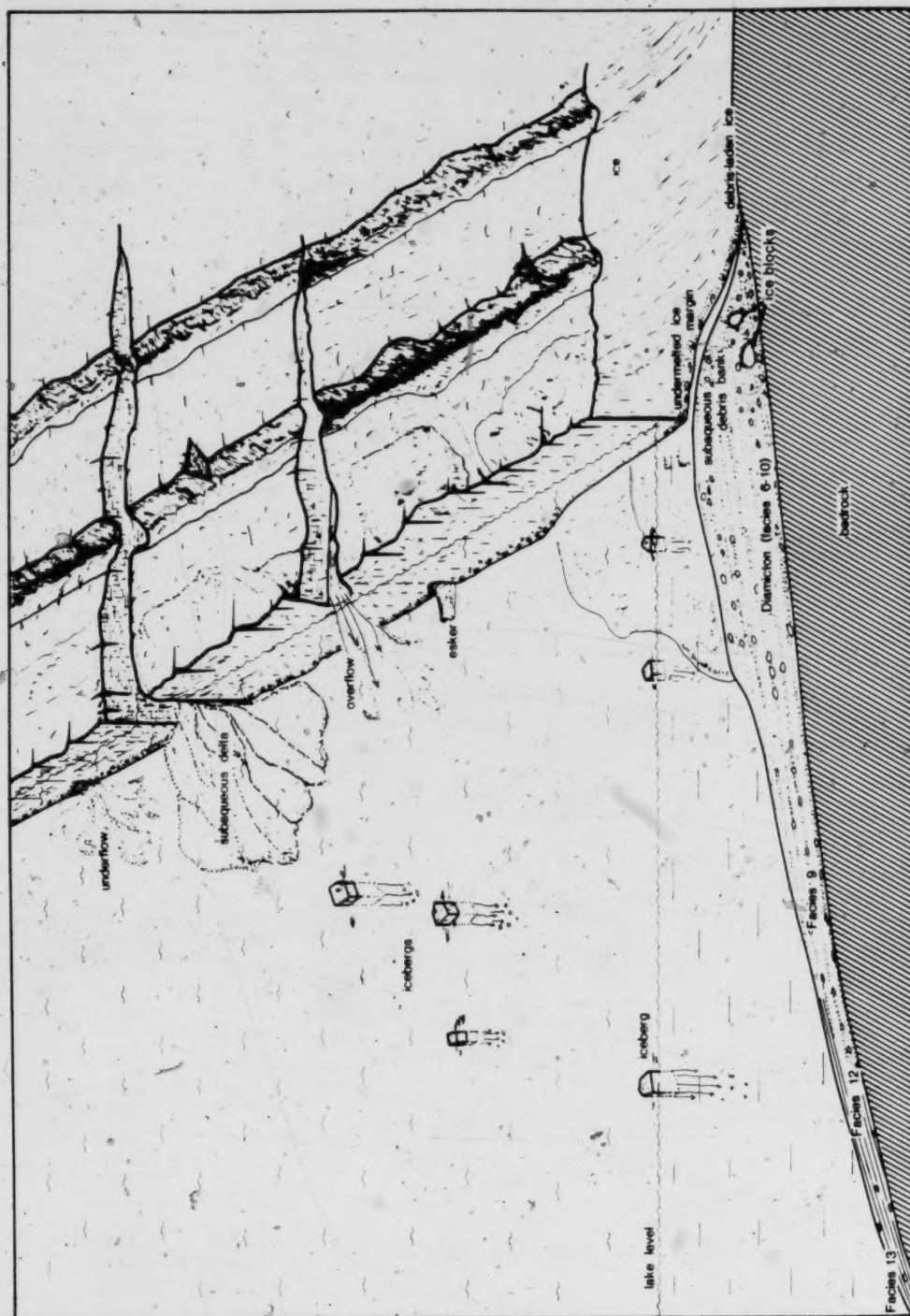
1. the facies
2. the vertical facies associations
3. the lateral facies associations
4. the production and shape of the hummocky terrain on the east side of the Battle River
5. The preservation of the facies associations in the hummocky terrain

DEPOSITIONAL SUMMARY FOR THE FACIES IN THE STUDY AREA

Blockage of the regional drainage by advance of Keewatin ice from the north east, resulted in the formation of short-lived proglacial lakes (Stalker, 1960; St. Onge, 1972). The elevations of the outlets of this lake (St. Onge, 1972) indicates that it was shallow 25 to 75m depth at a maximum. The shallow nature of the lake and its limited extent precludes the formation of ice shelves or slightly floating ice margins therefore the ice is grounded. Ice grounded in shallow lakes releases the bulk of its entrained debris at the grounding line through:

1. brash ice calving producing small icebergs which raft only a small amount of debris further into the lake basin (Sugden and John, 1976).
2. Undermelting of the ice margin at the grounding line producing large subaquatic moraines at the grounding line (Holdsworth, 1973a,b; Barnett and Holdsworth,

Figure 5.6. Block diagram showing the distribution of environments and the lateral associations of the facies observed in the study area.



BLOCK DIAGRAM OF THE DEPOSITION OF GLACIGENIC DEPOSITS FROM ICE
GROUNDED IN A SHALLOW ICE-PROXIMAL LAKE.

1974).

3. Sediment flows originating from the ice either subaerially or subaquatically also supply sediment to the grounding line (Evenson *et al.*, 1977).
4. Subglacial, englacial, and supraglacial streams flowing into the lake from the ice margin also add large quantities of fine sediment to the lake at this location.

Initially, sedimentation rates at the grounding line are high. Both undermelting and brash ice sedimentation would release diamicton pellets into the lake (Ovenshine, 1970). The high volume of sediment input and the rapid rate of deposition results in the formation of large mounds composed of oversteepened, water saturated sediments in which high pore water pressures are present. The sediments are prone to slumping (Gustavson, 1975; Middleton and Hampton, 1976), with the slumps rapidly transforming into subaqueous fluid debris flows (Morgenstern, 1967; Hampton, 1972). These flows deposit thin uniform beds of texturally homogeneous diamicton containing laminated silt and clay intraclasts, clay clasts, pebble-cored intraclasts, and diamicton pellets. The debris flows may generate density currents which deposit their sediments further in the lake basin (Hampton, 1972). Blocks of ice are buried by the debris flows. This initial deposit of oversaturated unstratified sediments represents Facies 6, the massive diamicton. Initially the high rate of sediment input from undermelting, calving, and slumping disrupts the bottom and turbidity current deposits and incorporates them into the diamicton forming an unstratified diamicton. As Facies 6 is non-stratified, dropstones released by icebergs will not form observable deformations within the deposit.

Powell (1979, 1981) describes areas in front of marine glaciers where calving is infrequent and inflow of streams minimal. In these locations quiet water deposition of silts occurs. Hickock *et al.*, (1979) also describe the interbedding of diamictons arising from subaquatic sediment flows and marine silts. If the introduction of debris through the various processes active at the grounding line is intermittent, silts deposited when the water was quiet will become interbedded with diamictons deposited by periodic slumping of material released at the grounding line. Facies 7 could be interpreted as the result of this alternation of quiet water and mass movement depositional processes.

With the passage of time the rate of sediment input from the processes at the grounding line decrease and conditions favoring failure (oversteepening, oversaturation,

and high pore pressures) are reduced resulting in a longer time period between mass movement events. The sediment flows are thinner, more fluid, and not as disruptive as the sediment flows of Facies 6. As the time interval between mass-movement events is longer the tops of the diamictos are winnowed for longer time periods producing small scale erosional features such as pebble lags, lee-side shadows and scours, and sand laminae which become intercalated with the diamictos. The increased time interval between mass movement events also makes it probable that deposits of a few of the low frequency of occurrence turbidity flows will be preserved in the deposit. These flows deposit proximal turbidite sediments (sands) near the grounding line and distal turbidite sediments (silts) further within the lake basin. With the formation and preservation of sand laminae, the deformations caused by the impact of dropstones and the drapes over the dropstones will be visible. Winnowing by bottom currents, deposition of proximal turbidites, and deposition of thin fluid sediment flows accounts for all the sedimentary structures observed in Facies 8. Further into the lake basin, distal turbidity currents deposit silts on top of the diamicton layers giving rise to Facies 9. In the center of the lake, distal turbidites (Facies 12), and rhythmites (Facies 13), are deposited.

As the ice front slowly wastes back, the grounding line moves to the east as does the locus of deposition of Facies 6 and 7. The previous grounding line is now distal and the more distal sediment flows and intercalated silts of Facies 9 will be deposited at this location.

Further reduction in the release of debris from the undermelted ice margin and increased stabilization of the sediment at the grounding line results in fewer mass movement events and a longer period of time for the deposition of turbidite sediments thereby forming the thick graded silt beds of Facies 10. The debris flows of Facies 10 differ from those of the previous facies as there is a higher volume of mud clasts and laminated silt and clay intraclasts indicating that some of the sediment composing the diamictos had previously been deposited as rhythmites in quiet water and subsequently remobilized by slumping and sediment flows. Eventually the final stage is reached when release of debris from the ice is minimal, and the debris at the grounding line stabilizes. As little sedimentation from the ice is taking place uninterrupted deposition of rhythmites (Facies 13) occurs. Iceberg sedimentation continues to deposit dropstones and diamicton

clots into the rhythmites.

Shifting the ice terminus causes the superposition of basinal deposits over ice contact deposits. The ridge-like subaquatic debris banks marking successive recessional positions of the ice sheet terminus were mantled by debris sufficiently thick to completely obscure their original cross-valley subaqueous moraines. Blocks of ice covered by debris will later melt out to form a hummocky topography.

APPLICATION TO OTHER AREAS

So far in this chapter only a general summary of the depositional processes and environments of the study area have been given. To develop a model for sedimentation from grounded ice into ice proximal glacial lakes requires a more general approach to be taken. Walker (1984 p. 4) states that a model must fulfill four purposes:

1. it must serve as a norm for the purpose of comparison,
2. it must serve as a framework for further observations,
3. it must act as a predictor in new situations,
4. it must serve as a base for hydrodynamic interpretation of the deposit.

Figure 5.7 schematically shows the development of the facies expected to form in an ice proximal lake in which the ice is grounded. It starts by depositing massive diamicton in the area undermelted at the grounding line and in front of the ice. Initially the high rate of sedimentation and the many mass movement events form only a massive deposit. As the rate of sedimentation slows, other sedimentological processes become more important such as winnowing by bottom currents and the deposition of proximal turbidite sands which form a deposit composed of diamictons intercalated with sand laminae. The proximal turbidites (sand laminae of facies 8) are replaced further in the lake by silts representing more distal turbidite sedimentation (silt laminae of facies 9). These silts are also interbedded with diamicton layers. Finally in the center of the lake basin, graded silts which may represent turbidity flows generated by the sediment flows are deposited. Rhythmic sedimentation occurs within the most distal part of the lake basin depositing the couplets of silt and clay. Wasting back of the ice front causes the facies to shift towards the new ice front position resulting in the superimposition of facies. Subaqueous deltas formerly located along the ice front are inundated by the basinal facies as are ice contact

deposits such as eskers.

The model proposed above fulfills the four requirements as stated by Walker (1984). A model such as the one proposed can only be of use if the conditions which cause it to occur are commonplace. In Alberta, blockage of the regional drainage by ice flowing from the northeast resulted in the formation of many proglacial and ice contact lakes. But formation of ice contact lakes would also occur in front of most ice sheets due to isostatic depression of the earth's crust (for example Glacial Lake Chicago in Wisconsin). From these two facts it can be concluded that the occurrence of lakes in front of ice is a very common if not ubiquitous occurrence. Sedimentation in these lakes could be similar to that described in this thesis. Because of this the model can act as a framework for future observations, and as a predictor in new situations. The model proposed also helps to explain the flow mechanisms which allow thin diamictos to be intercalated with sand and silt laminae. Lastly it is too early to tell if this model can act as a norm for the purposes of comparison. Preliminary investigation in other areas of Alberta has revealed that at least part of the sequence of glaciogenic diamictos is present. In the Villeneuve area, Fort Saskatchewan area, and near Edmonton, diamictos interbedded with silt beds were observed. The occurrence of similar sequences in the Paddle River area as described in this thesis has been mentioned to the author by the site geologist of the Paddle River Dam project (Tedder, 1982). At the present time the interpretation of glaciogenic diamictos is still in its infancy and few sequences have been described in which the diamictos intercalated with silt and sand laminae and with rhythmite beds have been interpreted in this manner. As the stratified diamictos described in this thesis closely resemble those described from other localities but which have been interpreted as meltout or lodgement tills, care must be taken to collect full and accurate descriptions of the deposits before any attempt to determine their genesis is made. Using this approach similar sequences of stratified sediments will be interpreted as glaciolacustrine deposits.

COMPARISON OF THE GROUNDED ICE SHEET MODEL DEVELOPED IN THIS THESIS TO A FLOATING ICE SHELF MODEL

The sedimentation model developed in this thesis describes sedimentation at the margin of an ice sheet grounded in a proglacial lake. Eyles and Eyles (1983); Eyles *et al.*,

(1983); and Eyles and Miall (1984) describe formation of subaquatic diamictons beneath a floating ice shelf. In their model the dominant means of sediment deposition are "rain-out" of sediment from the floating ice and influx of sediment-laden streams forming sediment plumes at many levels within the water column. Subsequent resedimentation by various mass-movement processes redistributes this sediment over the lake bottom. Traction currents winnow the tops of the deposits forming sand laminae and lenses and turbidity currents also deposit sands and silt laminae within the deposit. Eyles and Eyles (1984, p. 188-189) state that

Deposition from grounded or partially floating ice is prohibited by the presence within the diamictons of undisturbed lenses of starved ripples, loaded sand pillows and ripples, silt laminae, silt clay and diamicton intraclasts, graded laminations of silt and clay deposited by turbidites, the presence of interbedded and loaded basal contacts with underlying deltaic sands, and loaded and interbedded upper contacts with deltaic sands or laminated silty clays.

Eyles and Eyles (1983) use the presence of stable remnant magnetism to support the floating ice shelf model. Use of these features to infer that a sequence of glacial deposits formed beneath a floating ice shelf has been sharply criticized in the literature (Karrow *et al.*, 1984). The loading features observed within many of the units described by Eyles and Eyles (1983) do not indicate suspension sedimentation. Rather, they indicate that the material was water-saturated and plastic at the time these features formed, which is also the case for subaqueous diamictons deposited from a grounded ice sheet by sediment flows. The remnant paleo-magnetism simply indicates a water-saturated deposit with no indication of the genesis of the sediment (Gravenor, 1984 in Karrow *et al.*, 1984). Silt and sand laminae are also non-diagnostic for a floating ice shelf environment as they are common in many glacial environments as described in Chapter 3 and in the discussion of facies 6 and 8 in this thesis. Similarly the presence of graded silt and clay laminations indicates only a lacustrine depositional environment and their interbedding with glacial diamictons indicates only a subaqueous glacial environment, it gives no indication whether the ice was floating or grounded. Eyles and Eyles (1983, 1984) offer no criteria to distinguish sand and silt laminae formed beneath a floating ice shelf from laminae

formed in other glacial environments. In the discussion of the deposition of Facies 6 and 8, the deposition of silt and clay clasts and diamicton intraclasts was described for the grounded ice scenario. The diamicton pellets and other intraclasts within the graded silt laminae could be formed by erosion of the tops of the diamictons by the turbidity currents which deposited the graded silt and clay laminations (Banerjee, 1973). The presence of intraclasts in either the diamictons or the graded silt laminae is therefore not diagnostic of ice-shelf sedimentation as maintained by Eyles and Eyles (1983, 1984).

Powell (1984) states that the following limiting conditions must be met before ice shelves can form:

1. sheltered bays to protect the ice shelves from forces which would tend to break up the shelf,
2. anchor points for protection against break-up,
3. high input of ice from the grounding line to counteract the ablation processes of calving and subglacial and / or supraglacial melting,
4. most of the upper surface must be an accumulation area to counteract the ablation processes,
5. the ice shelf must be comprised of cold ice as warm ice is more prone to break-up due to its lower tensile strength.

Because of these limiting palaeo-geographical, palaeo-glacial, and palaeo-climatic conditions, ice shelf environments are very restricted in regard to their distribution when compared to the more common grounded tidewater glaciers which are not restricted by similar limiting conditions. Eyles and Eyles (1983, 1984) do not demonstrate that the conditions in the Great Lakes were conducive to the formation of floating ice shelves.

As already stated in the opening of this chapter, a model must perform four functions (Walker, 1984). The floating ice shelf model of Eyles and Eyles (1983), Eyles *et al.* (1984) and Eyles and Miall (1984) does not meet the first function which is to act as a norm to which other sedimentary sequences can be compared. It cannot act as a norm as the features used to define the model are not diagnostic of sedimentation beneath a floating ice sheet. These sedimentary features can also be produced by sedimentation from grounded ice sheets in both the pro-glacial lake and the glacial-marine environments. If a model cannot discriminate between two different possibilities it cannot act as a

framework or a guide for further studies, it cannot be a predictor in new situations, and it cannot act as a basis for interpreting the hydrodynamics of the environment.

Finally, Eyles and Miall (1984, p. 28) state:

... a detailed facies model for the sub-ice shelf environment awaits documentation but ... the importance of such sedimentation in the rock record (as evidenced by the popularity of the ice shelf model) has been exaggerated

...

In this thesis sedimentation from an ice sheet grounded in a proglacial lake was proposed for the following reasons:

1. the physical setting of the lake such as its shallow nature and limited areal extent does not meet the restrictions as set forth by Powell (1984) for the generation of a floating ice sheet,
2. the homogeneous nature of the diamictons and their sharp contacts favor a sediment flow origin as "rain-out" from a floating ice shelf would tend to produce bimodal sediments with discontinuous, irregular contacts between strata (Anderson *et al.*, 1980 a, b).
3. "Rain-out" sediments would also be expected to have poorly defined stratification produced by fall sorting, melt water sediment plumes and winnowing in the water column or along the bottom of the lake by currents (Powell, 1984). The stratification within the facies of the study area is well-defined and regular.

At present, it is extremely difficult to differentiate deposits of grounded ice sheets from those of floating ice sheets. This thesis is an initial attempt to do so using a limited set of sedimentary criteria. The problem of differentiating these two environments will only be resolved when detailed sedimentological descriptions of sub-shelf sediments and sediments originating from grounded ice sheets are available for comparison allowing more diagnostic sedimentary criteria to be observed.

New models of ice shelf sedimentation (Orheim and Elverhoi, 1981; Anderson *et al.*, 1982 a, b; Powell, 1984) indicate that the bulk of the sedimentation occurs at the grounding line forming sub-shelf morainal banks (Powell, 1984). These sub-shelf debris banks are affected by the same processes which affect debris

banks formed in front of grounded ice sheets which lack floating ice. Because of this overlap in process differentiation of these two environments will only be possible if diagnostic sedimentary features for each environment are discovered.

VI. QUATERNARY HISTORY OF THE STUDY AREA

The exact timing of the deglaciation of the area is not known. St. Onge (1972) has established a seven phase sequence of appearance and drainage of glacial lakes in North Central Alberta. Glacial Lakes Malmo and New Norway were in existence in the study area during Phases 3 and 4 of this sequence. St. Onge (1972 p. 7) states that these lakes had drained before the beginning of Phase 5 of his sequence. St. Onge (1972) reports radiocarbon dates for Phase 2 as 13,500 for the beginning of Phase 2 and 10,700 or 11,400 years BP for the beginning of Phase 7. This clearly indicates that deglaciation of the study area was rapid and places the time of deglaciation between these dates. The dates show that this deglaciation must have occurred at the end of the Late Wisconsinan time period.

PHASE 1

Initially the study area was glaciated by Keewatin ice flowing from the north east. The planar contact observed below Facies 12 in the West Pit section would most likely have been formed by an overriding ice sheet. Formation of the lake (Glacial Lake Malmo) was initiated with the onset of ablation of the ice sheet (Figures 6.1a, 6.2a).

PHASE 2

Further retreat of the ice caused the ice front to waste back to the west side of the Battle River as indicated by Facies 3, the esker deposit at the Old Pit section (Figures 6.1b, 6.2b).

PHASE 3

During Phase 3 the ice terminus retreated to a new grounding line (Figure 6.3a 6.4a). Sediment released at this new grounding line supplies the sediments for the formation by Facies 6, 7, 8, 9, 10, and 13 which drape Facies 3. Facies 12 of the Glaciolacustrine zone may be formed from turbidity currents generated by the mass movement events which deposited the diamictos of the Diamicton-Glaciolacustrine Zone.

Figure 6.1a Map showing the approximate location of the ice margin during Phase 1 of deglaciation. Glacial Lake-Malmo beginning to form in the study area.

Figure 6.1b Map showing the approximate location of the ice margin during Phase 2 of deglaciation. Glacial Lake Malmo expanded at this time.

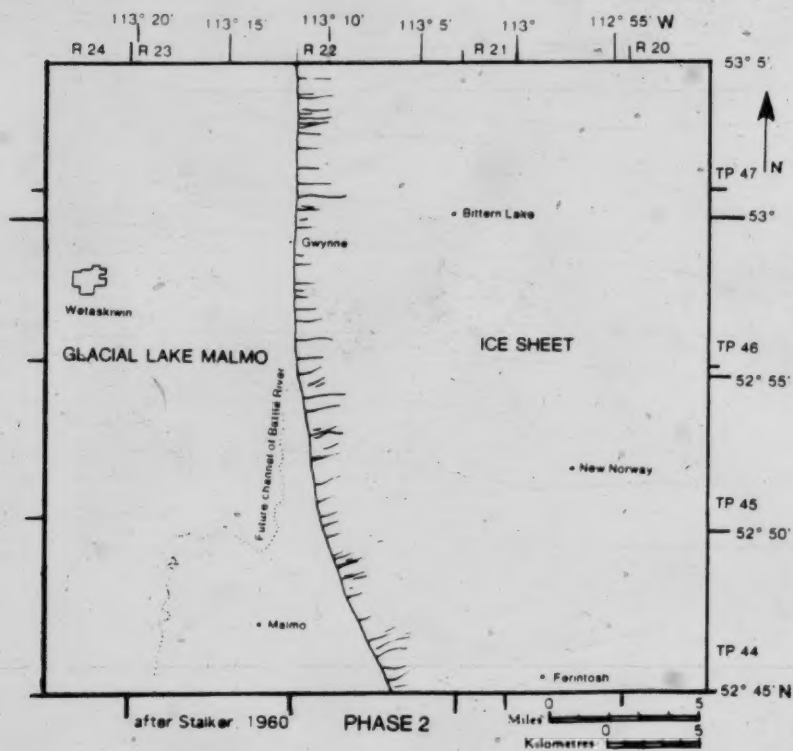
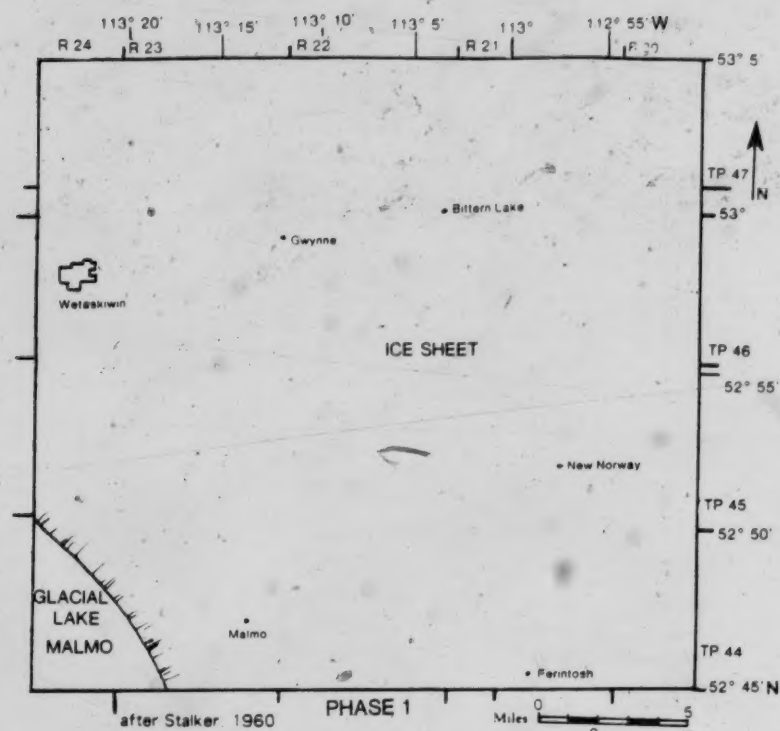


Figure 6.2a, Phase 1-2 initiation of retreat of Keewatin Ice from the study area and formation of an ice-proximal glacial lake. Ice retreats from the far west part of the study area without depositing diamictons. Later undercutting of the ice margin releases debris to form a subaquatic moraine.

Figure 6.2b, Continued retreat of the ice. Deposition of diamicton continues. Lateral superimposition of the basinal facies over the more proximal diamicton facies.

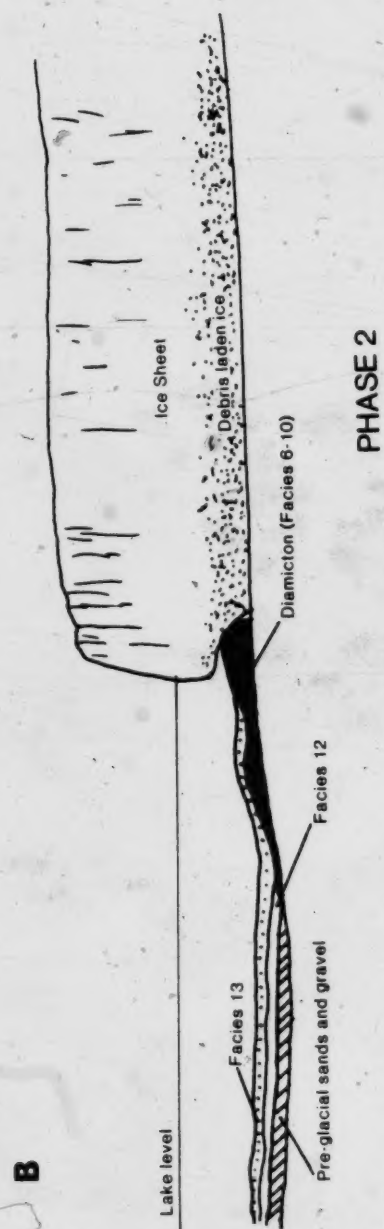
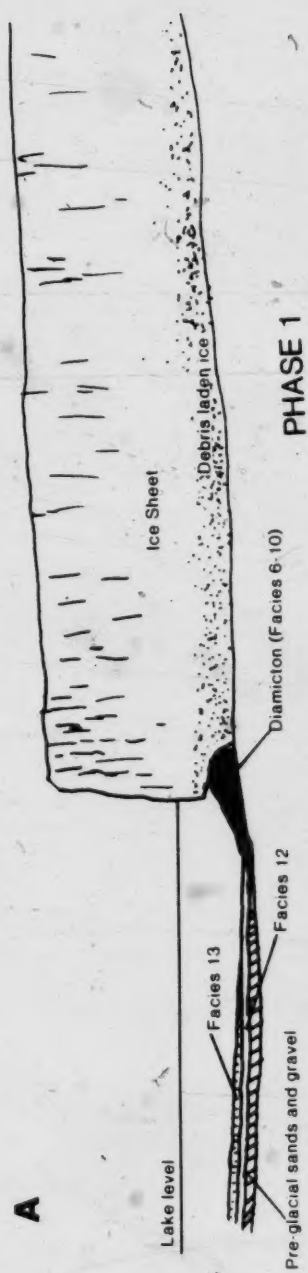
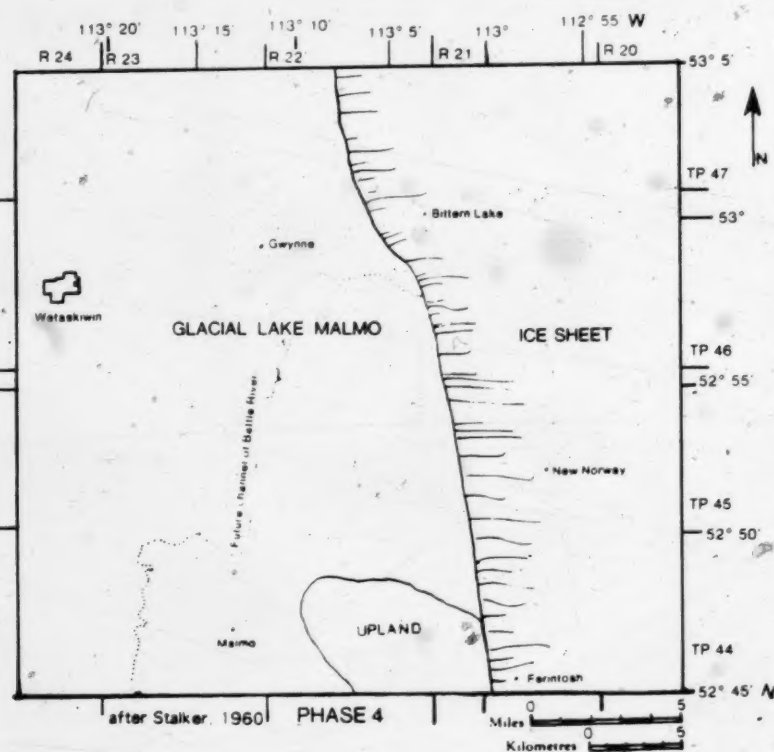
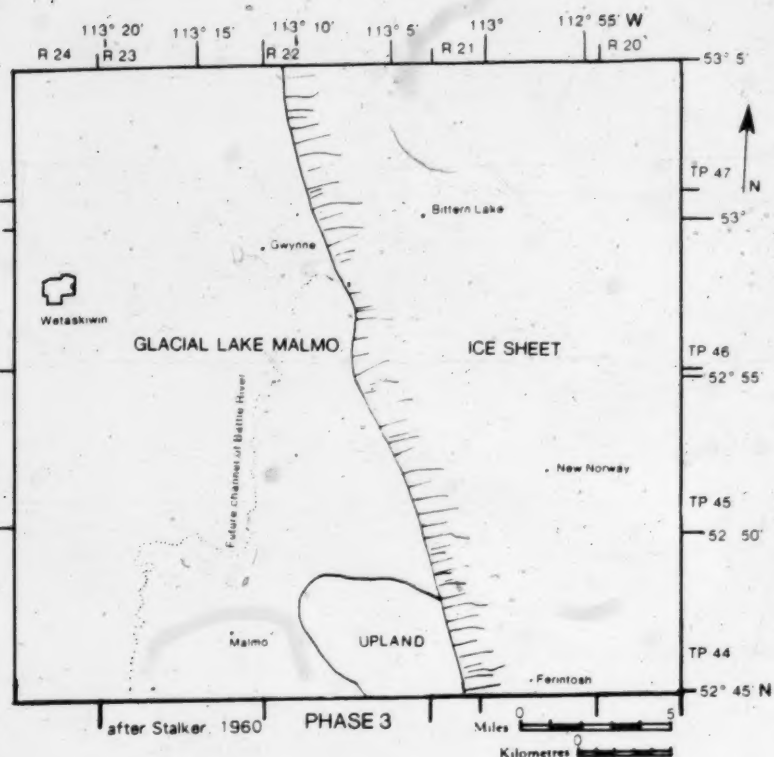


Figure 6.3a. Map showing the location of the ice margin during Phase 3 of deglaciation. A small upland area is subareally exposed at this time and will expand as time passes.

Figure 6.3b. Map showing the location of the ice margin during the late stages of Phase 4; immediately prior to drainage of the lake.



PHASE 4

A further retreat of the ice margin (Figure 6.3b, 6.4b) allowed the inundation of the glacial delta (Facies 4) and the outwash plain sediments (Facies 2) beneath a silty glaciolacustrine diamicton (Facies 5). This retreat probably coincided with the deposition of the rhythmites (Facies 13) over the glaciogenic diamictons of region 3 and deposition of Facies 5 over Facies 2 and Facies 4.

PHASE 5

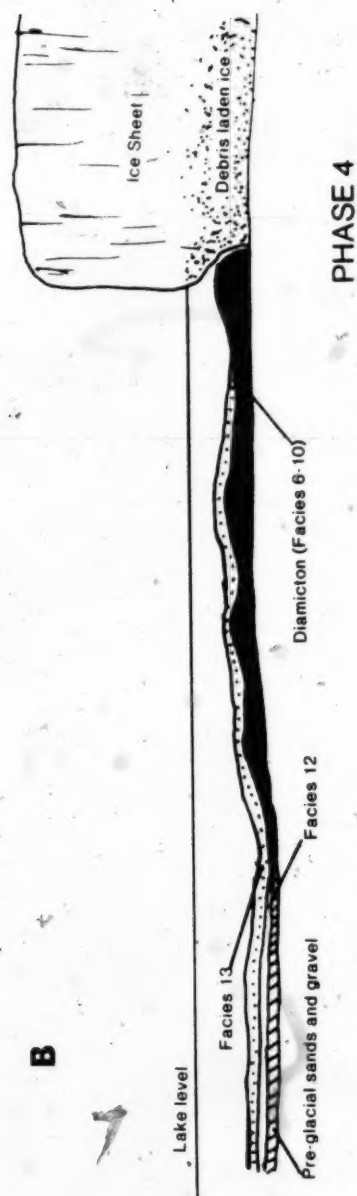
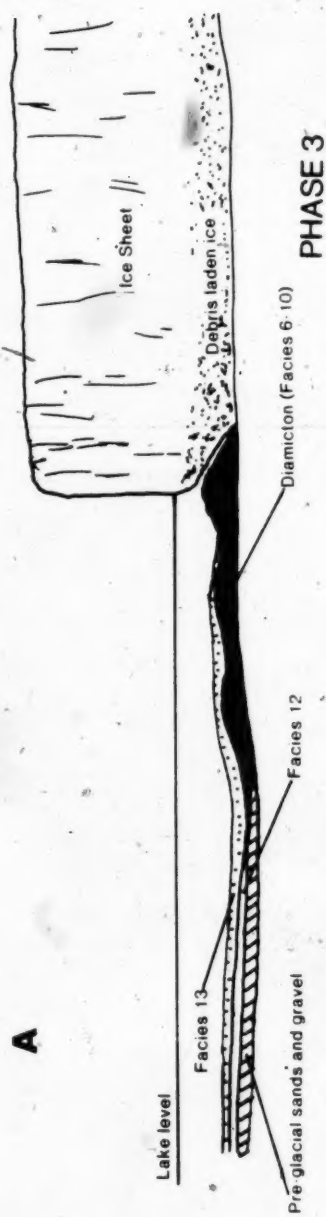
Figure 6.6a shows the deposits of the study area during late Phase 4 and early Phase 5 immediately before drainage of the lake. Continued ice retreat moved the ice to the eastern part of the study area (Figure 6.5a), exposed Facies 1 and allowed the lake to drain through an outlet located at Ferintosh which has an elevation of 2300 ft. A period of instability occurred immediately upon drainage as the landscape adjusted to subaerial environmental conditions. The Battle River meandered through the study area leaving an intermittent gravel lag but rapidly incised its valley in the previous channel of the pre-glacial Red Deer River and initiated the slumping which formed Facies 11. Dunes are also formed at this time from sediments exposed by the drainage of the lake.

PHASE 6

The terrain continued to stabilize with the beginning of the meltout of the buried ice blocks which initiated the formation of the hummocky terrain of the south and central parts of the study area (Figures 6.5b and 6.6b). Dunes formed from sands contained in the newly exposed lake deposits. Soil formation began and vegetation returned to the area. The water table dropped causing desiccation of the upper parts of the sections and destruction of their sedimentary features. Oxidation of the desiccated upper parts of the sections altered their color to a uniform tan further reducing the visibility of their sedimentary features. Subaerial erosion and stream entrenchment continues to the present time.

Figure 6.4a. Continued retreat of the ice permits the continuing deposition of subaquatic glacial diamictites within the lake.

Figure 6.4b. Schematic drawing of the distribution of sediments in the lake immediately before lake drainage through the Ferintosh Outlet during Phase 5.



Immediately before draining of the lake.

Figure 6.5a. Map of the study area during Phase 5. Drainage of the Glacial Lake Edmonton and Leduc into Glacial Lake New Norway incised the Gwynne Outlet. At the end of this phase Glacial Lake New Norway drains through the Ferintosh Outlet.

Figure 6.5b. Map of the area after deglaciation and drainage of the lakes, showing the location of the Battle River.

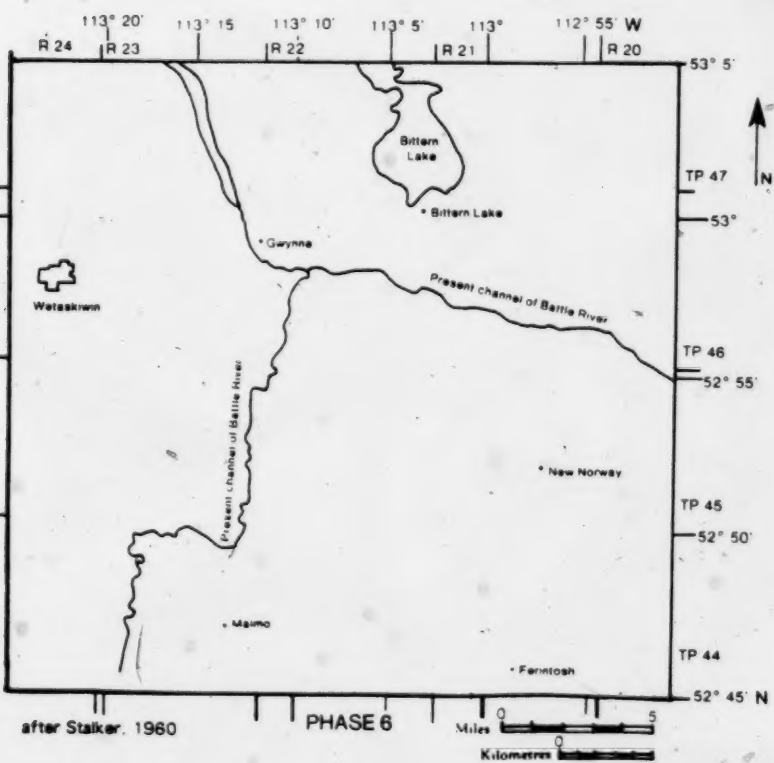
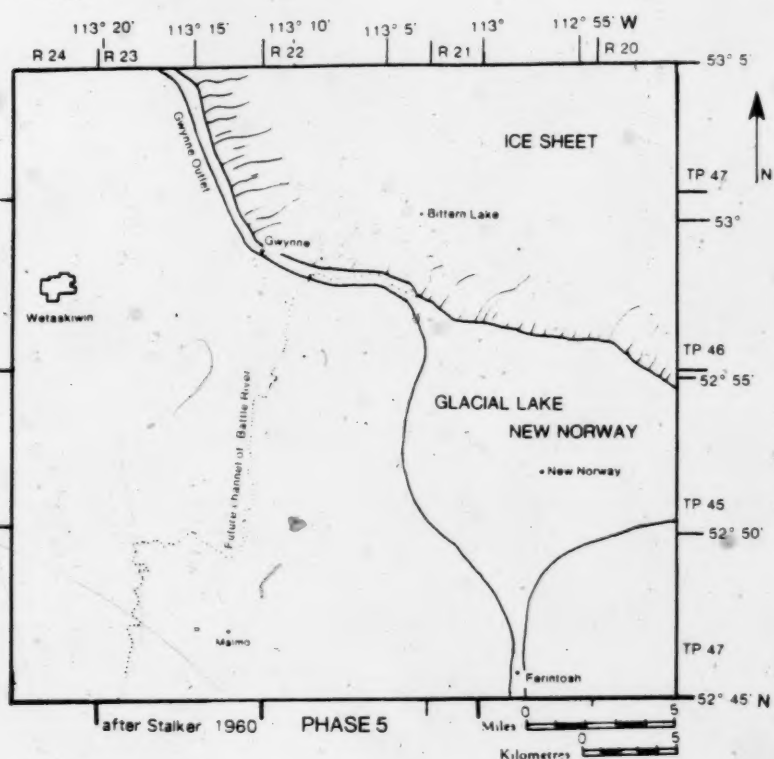


Figure 6.6a. Expanded view of the glacial deposits deposited during late Phase 4 and early Phase 5 before drainage of the lake. Facies 13 which caps the deposits is emplaced just prior to drainage of the lake.

Figure 6.6b. Formation of the present day topography is related to the drainage of the glacial lakes and the meltout of the buried iceblocks. Drainage of the glacial lakes allows incision of the Battle River and the formation of the Battle River valley with slumping and other mass movements occurring along the valley walls. Meltout of the buried ice blocks results in the formation of the hummocky topography in the central part of the study area. The meltout of the ice blocks occurred over a long timespan due to the insulating effects of the overlying sediments.

A

PHASE 4

Glacigenic deposits immediately before drainage of the lake.



B

PHASE 6

Glacigenic deposits after lake drainage, incision of the Battle River, and meltout of ice blocks.



VII. CONCLUSIONS

Several conclusions regarding the deposition of glacial diamictos, glaciolacustrine sedimentation, the pattern of late Pleistocene deglaciation in the study area, and the facies approach to studying glacial deposits can be made.

A. SEDIMENTOLOGY WITHIN THE STUDY AREA

1. Thirteen facies were identified in the study area representing direct ice, fluvioglacial, and glaciolacustrine deposition. These facies give an incomplete transect from the ice into the center of a proglacial lake. The Glacio-tectonic Zone 1, containing Facies 1 represents the margin of an ice sheet. The stratified sorted facies of the Glaciofluvial Zone, containing Facies 2, 3, and 4, represent glaciofluvial deposition in an ice-contact ice-proximal location. The diamicton facies observed in the center of the study area were deposited in a glaciolacustrine setting. The Diamicton-Glaciolacustrine Zone contains the diamicton facies which have been interpreted as forming in a subaquatic environment near the terminus of a grounded ice sheet. They were deposited primarily by sediment flows, with minor amounts of the deposits originating from iceberg rafting and turbid interflows. Some winnowing of the diamictos of facies 8 by bottom currents is also likely. The Glaciolacustrine Zone represents glaciolacustrine deposition by density underflows in the central part of an ice-proximal lake. These density underflows may have been generated by the slumps and sediment flows of the Diamicton-Glaciolacustrine Zone and therefore maybe their equivalents. There is also a suspension component to the deposits of this zone.
2. Tills "sensu stricto" are absent from the study area. In the Glaciolacustrine Zone the rhythmic sediments have a sharp planar unconformable contact with the pre-glacial sands and gravels below them. This contact probably represents planation by an overriding ice sheet but no till was deposited. The diamictos of the Diamicton-Glaciolacustrine Zone are interpreted as representing deposition by subaquatic sediment flows and do not represent direct ice sheet deposition. The reason tills are absent from the study area is unknown but indicates that ice sheets can override and retreat from an area without depositing tills to mark their passage.

3. The importance of proglacial lake sedimentation in depositing complex sequences of glacial diamictites is well illustrated by the study area. Proglacial lakes are common in areas such as Alberta where the regional drainage is blocked by advancing ice sheets. They may occur in front of all ice sheets due to isostatic depression of the earth's crust. The existence of proglacial ice contact lakes initiates the conditions conducive to the deposition of waterlain diamictites. Facies similar to those observed in the study area have also been observed in several other localities in central Alberta (Villeneuve Pit Sites, North Sask. River near Clover Bar, Fort Saskatchewan, Big Bend section, and in large exposures in the Medicine Hat and Lethbridge areas. While no attempt was made here to extend the interpretations of the facies in the study area to these other localities, the existence of similar sequences of glacial deposits indicates that the deposition of waterlain diamictites may be very important in other areas of Alberta and other parts of Western Canada. Re-interpretation of glacial deposits believed to be tills as subaquatic diamictites may greatly affect the existing glacial chronology of western Canada as well as beliefs on the extent of previous ice sheets and the ice-flow dynamics of the ice sheets in Western Canada.
4. The utility of the model proposed in this thesis for use in interpreting sequences of stratified diamictites can only be tested when more sedimentological studies of glacial sediments are undertaken.
5. Interpretations of Quaternary aged diamictites may also be relevant to the interpretation of Pre-Paleozoic glaciations as many of them are interbedded sequences of diamictites and sorted sediments which have often been interpreted as glaciomarine or glaciolacustrine in origin.
6. In the study of diamictite facies individual features are not diagnostic but assemblages of features can be used to determine the genesis of diamictite deposits. Textural studies used in conjunction with other properties are useful.
7. The destruction of sedimentary features by desiccation and oxidation has important implications to the study of glacial diamictites. The total destruction of the features as observed in the study area indicates that highly altered diamictite deposits may be impossible to identify on the basis of their remaining sedimentary

features and that the existence of this type of alteration must be realized and identified in the field to prevent misinterpretation of deposits.

8. In the study area Warren 1956, Stalker 1960, Tedder *et al.* 1982 identified an upper brown till overlying a gray till. The upper brown till is the result of oxidation due to a drop in the watertable. This is indicated by the continuation of facies from the lower gray unit to the upper brown unit and the relationship between the brown unit and joints and fractures along which it extends itself. Therefore in the study area these units are nondepositional.
9. The use of thin sections for the examination of glacial diamictites is a promising area of research which may result in identification of sedimentary features which are characteristic of the different diamictite types. Use of thin sections for the examination of diamictites intercalated with laminae of sand or silt allows the precise nature of the contacts between the components to be observed. Sedimentary structures within the laminae which may be critical to their interpretation can also be observed. Because of this more precise identification of the deposits can be made.
10. In this study emphasis was placed on the sedimentological interpretation of the different laminae which make up only a minor part of the deposit but which are crucial to the correct interpretation of the deposit. These laminae may also be important in the groundwater and engineering studies of tills as they may significantly affect the groundwater flow patterns or the engineering characteristics of the material therefore their recognition in section and borehole may be very important.
11. Airphoto interpretation of the geomorphology of an area is useful for initially dividing the area into regions. But many geomorphic features have the same geomorphic expression but are composed of different materials or have formed through different processes and therefore field investigation must be undertaken to determine if features with a similar look are the same. In the study area there are three hummocky terrain types each of which originated by different processes. The contorted local bedrock hummocks are due to glaciotectionic deformation, while the hummocks composed of stratified sediments and those composed of diamictites are due to meltout of buried ice blocks. Caution should be used in air photo

interpretation as differentiating the different types of hummocky terrain may only be possible through field checking.

12. The origin of the hummocks in Regions 2 and 3 of the study area departs from the relief inversion theory of Gravenor and Kupsch (1959). No evidence of relief inversion was observed. Preservation of the stratigraphic sequence was observed in the hummocks. In addition to this the hummocks form a uniform upper surface which is below the level of the lake. Flat topped hummocks have been interpreted as being planed off by over-riding ice sheets but only deposition of uniform thicknesses of sediments over stranded ice blocks in the glaciolacustrine environment can explain preservation of the sedimentary features and stratigraphic sequence within the hummocks.

B. RECOMMENDATIONS FOR FURTHER RESEARCH

1. Soft sediment clasts may be a diagnostic indicator of subaquatic sedimentation but further studies should be undertaken to ascertain that their presence diagnostically indicates glaciolacustrine deposition.
2. The use of thin sections of glacial diamictites promises the development of further criteria to establish the genesis of glacial diamictites and may be especially useful in the study of massive diamictites.
3. More data is needed on many aspects of the deposition of both glacial and non-glacial diamictites. Process studies are needed on the deposits of debris flows in which the sedimentary features of their deposits are described in detail. Thin sections should be made for the description of the microfabric and microstructural features of the deposits. Further investigations such as Lawson (1979) which trace the debris from the ice to the final deposit are required.

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APPENDIX 1: DIAGRAMS OF THE MAJOR SECTIONS DISCUSSED IN THE THESIS

This appendix contains section diagrams of the major sections discussed in this thesis.

Figure A 1.1 Section diagram of the New Pit North Section.

-  macrofabric location (dataset number to left of symbol)
 -  oriented block sample location
 -  texture sample location
 -  pebble lithology sample
 - Plate

 location of plates used in the text
- Plate 1= Plate 4.27b p. 149(top)
- Plate 2= Plate 4.24, p. 139
- Plate 3= Plate 4.25 p. 141
- Plate 4= Plate 4.26 p. 143
- Plate 5= Plate 4.13 p. 95
- Plate 6= Plate 4.27a p. 149(bottom)

New Pit North

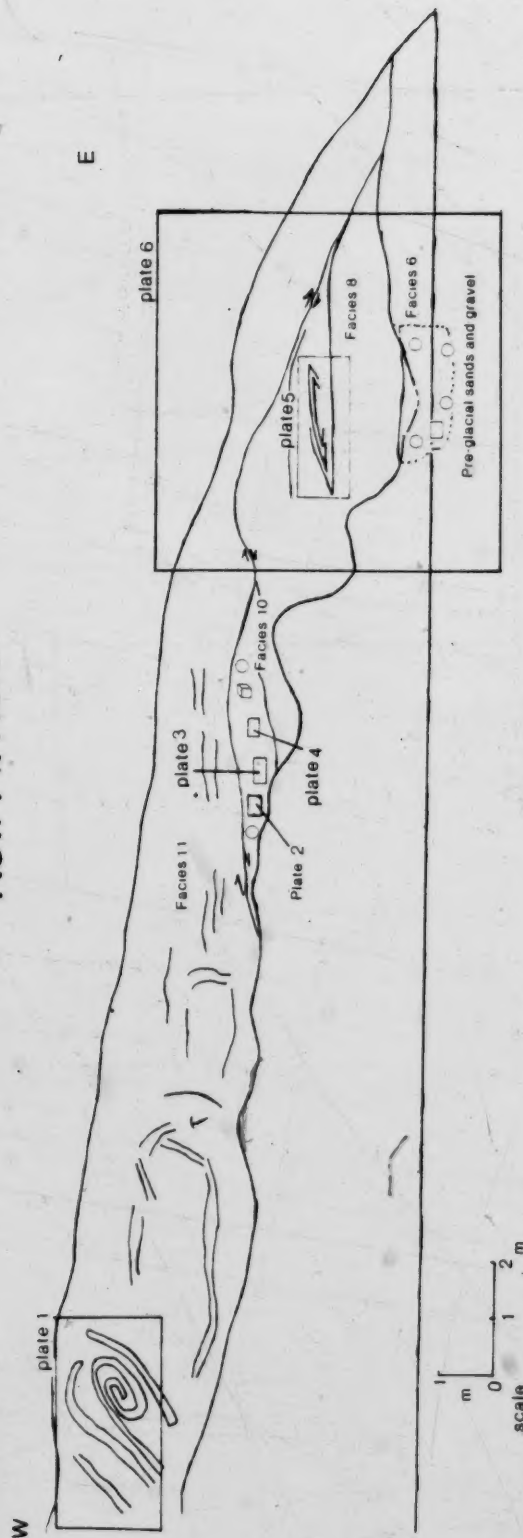


Figure A 1.2 Section-diagram of the New Pit South Section.

-  macrofabric location (number of dataset to the left of symbol)
 -  oriented block sample location
 -  texture sample location
 -  pebble lithology sample
 -  location of plates used in the text
- Plate 1= Plate 4.19 p.125
- Plate 2= Plate 4.18 p.123
- Plate 3= Plate 4.9 p.83
- Plate 4= Plate 4.10 p.85

New Pit South

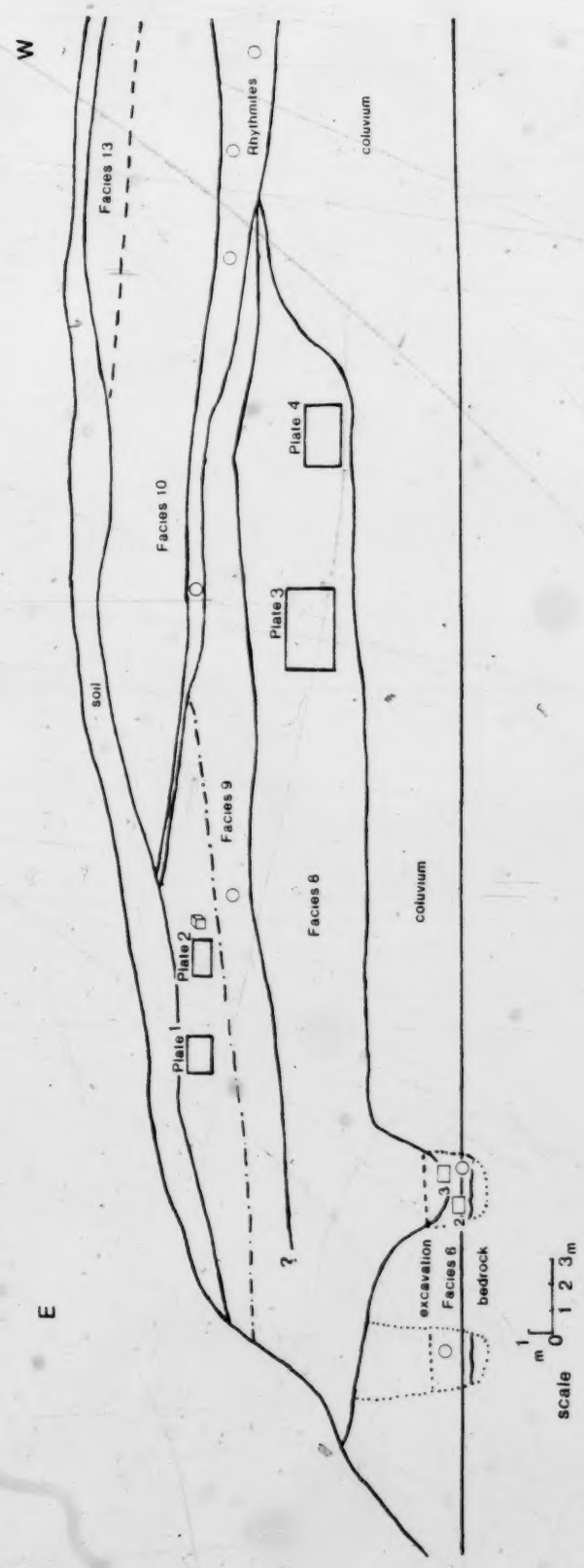


Figure A 1.3 Section diagram of the New Pit West Section.

- ☐ macrofabric location (dataset number to left of symbol)
- ☒ oriented block sample location
- ☐ texture sample location
- pebble lithology sample
- location of Alberta Environment Borehole 32.
- Plate ☐ location of plates used in the text

Plate 1= Plate 4.11 p.88

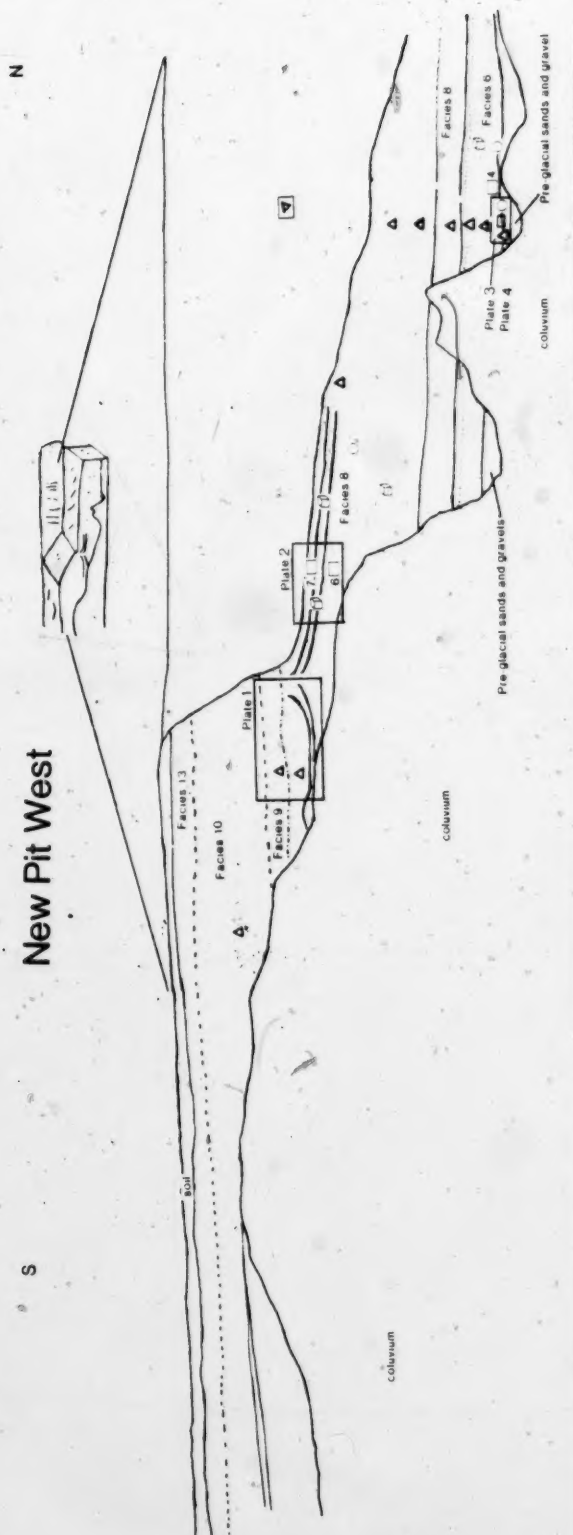
Plate 2= Plate 4.10 p.85

Plate 3= Plate 4.4 p.54

Plate 4= Plate 4.5 p.56

Inset on the top is a 3-D view of the section.

New Pit West



scale m
0 1 2 3

Figure A 1.4 Section diagram of the Old Pit Section.

-  macrofabric location (dataset number to left of symbol)
-  oriented block sample location
-  texture sample location
-  pebble lithology sample
-  location of plates used in the text

Plate 1= Plate 4.22 p.135

Plate 2= Plate 4.23 p.137

Plate 3= Plate 4.3 p.50

The section has been split in half at the crenulated lines allow reproduction on a single page.

Old Pit Section

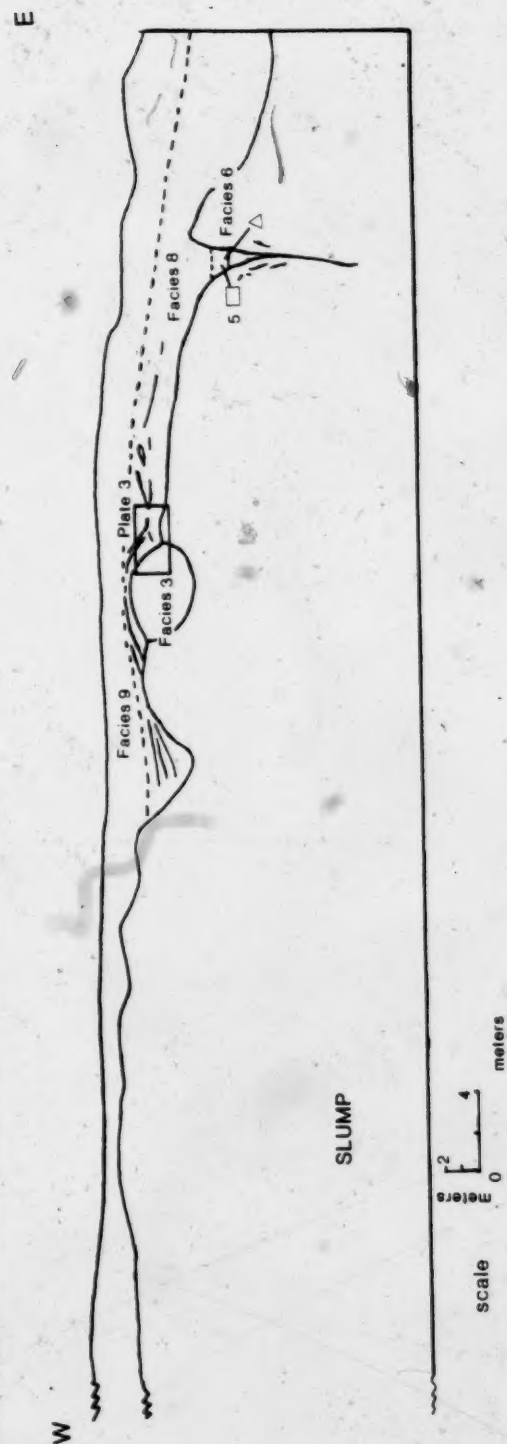
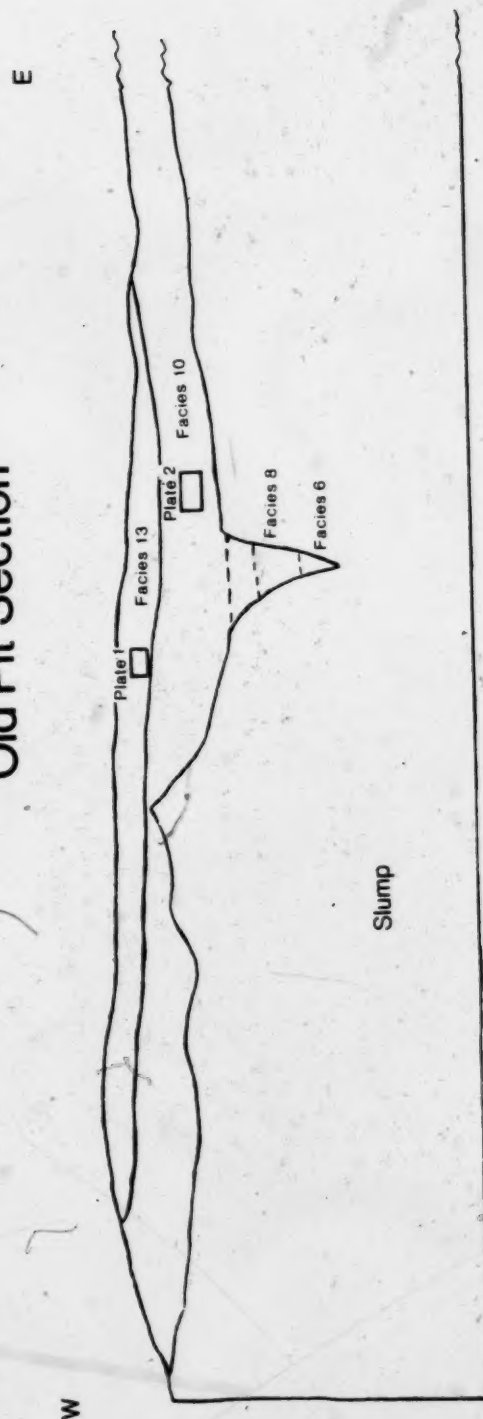


Figure A 1.5 Section diagram of the Riverbend 1 Section.

- macrofabric location (dataset number to left of symbol)
- ▣ oriented block sample location
- texture sample location
- △ pebble lithology sample

Riverbend 1

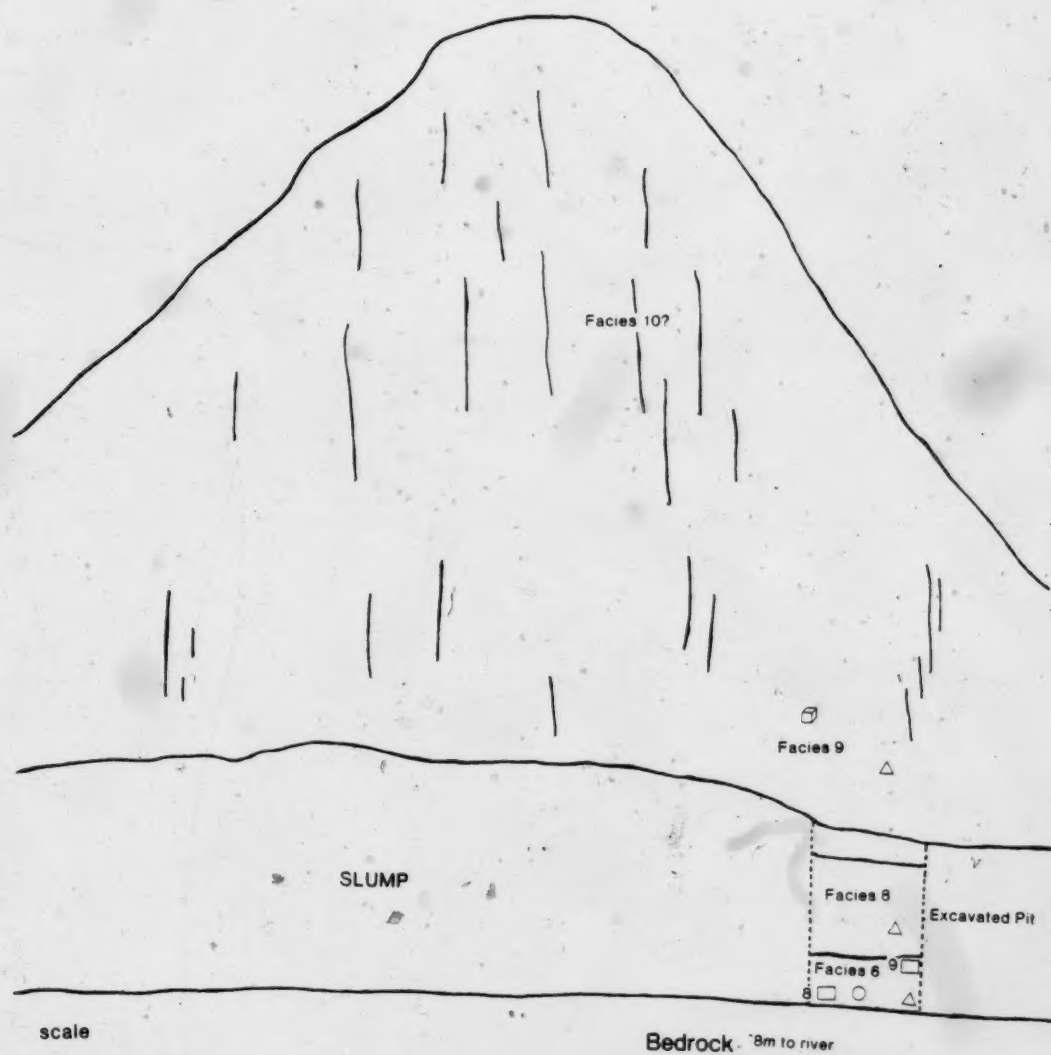
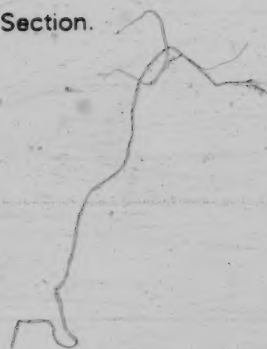
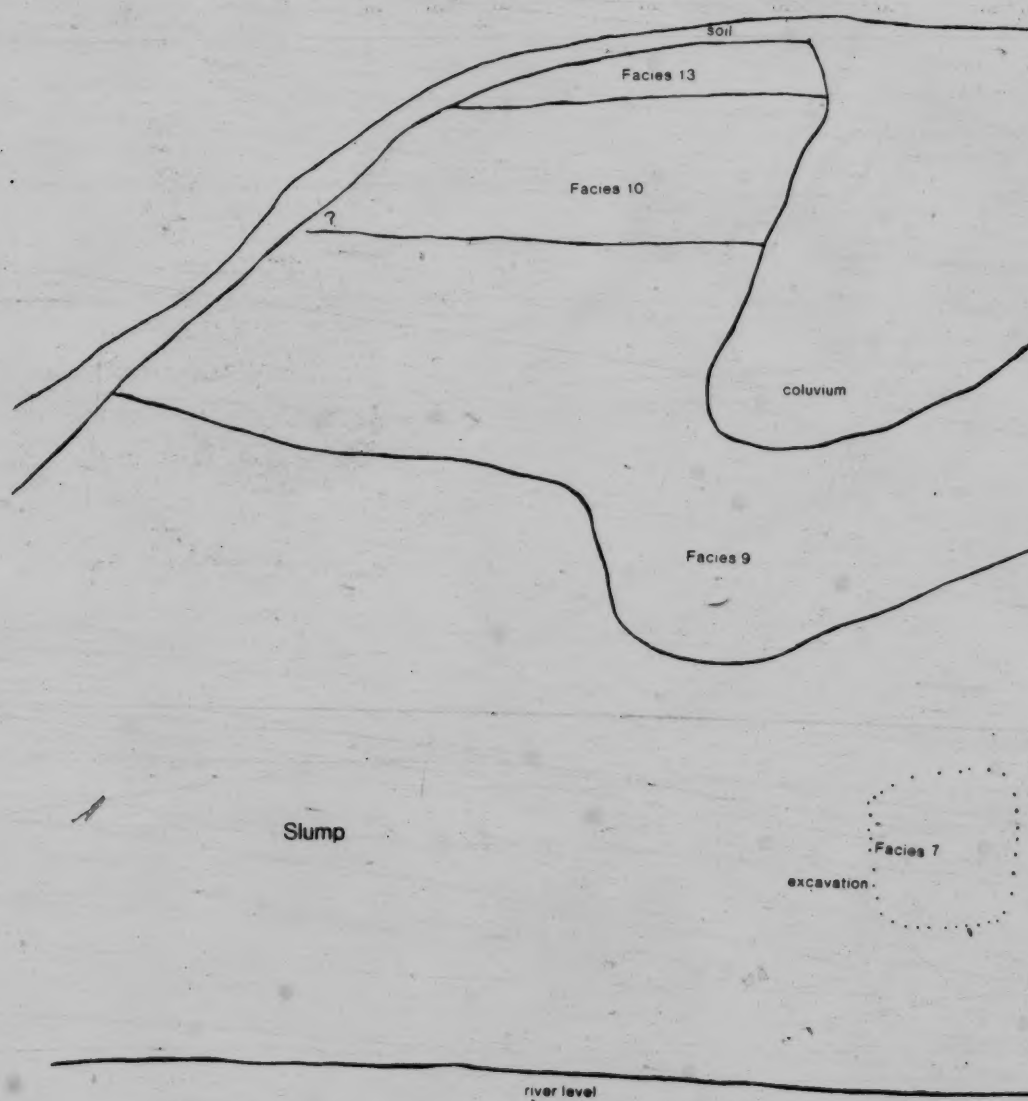


Figure A 1.6 Section diagram of the Riverbend 2 Section.

- macrofabric location
- ▣ oriented block sample location
- texture sample location
- △ pebble lithology sample

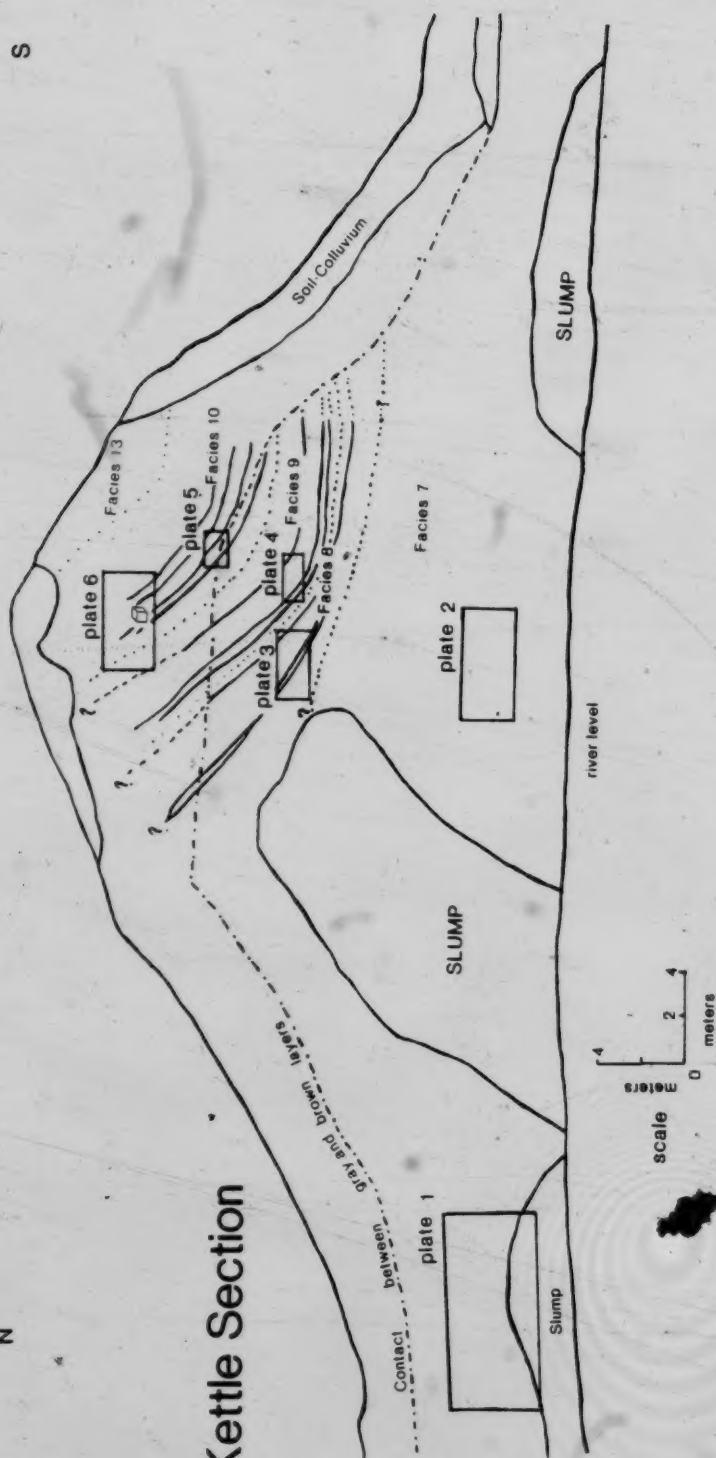


RIVERBEND 2



Main Section

Kettle Section



APPENDIX 2: PRODUCTION OF THIN SECTIONS

Thin sections were produced for the examination of the sediments in detail and for the measurement of microfabrics. Oriented blocks were obtained in the field either by breaking cohesive samples along joints or by careful removal of uncohesive samples by using a small monolith box such as those used for soil sampling. In the lab the samples were removed from the sampling containers and allowed to air dry for several days. Then the samples are dried in a 75 ° C oven for 24 hours. Once the samples are dry; they are placed in a plastic lined container on corrugated cardboard strips which allows the impregnating resin to penetrate the sample from below. The sample is then placed in a vacuum chamber which has been preheated to 75° C. When the sample is initially placed in the chamber a separatory funnel is inserted through an inlet in the top of the chamber. The spout of the funnel is placed alongside the sample as close to the base of the sample as possible. This facilitates impregnation by allowing the resin to rise up into the sample. Introducing the resin on top of the sample gives poor impregnation results.

Once the funnel has been inserted the chamber is sealed and the sample is placed under full vacuum for at least 20 minutes. Then the vacuum is reduced to 20 inches of mercury to prevent the resin from boiling when it is introduced. While the air in the sample is being removed by the vacuum, the resin is prepared using a 3M casting resin with a mixture of 3 parts resin to 2 parts hardener. This mixture is heated on a hot plate to 90° C then slowly introduced to the sample through the separatory funnel at a rate of approx. 30 ml per minute. After the resin has been introduced, air is slowly let into the chamber. The sample is removed from the chamber and placed into a 75° C oven for 24 hours to cure the resin. It is possible to cut the sample immediately but samples which have cured for several weeks to months produce better final results. For the best impregnation results the sample should be thin approx. 6-10 cm thick and 6-15 cm high, and 6-10 cm wide. A sample which is square is easiest to orient for cutting after it has been impregnated. The funnel should be placed alongside the sample as low as it can. Sample numbers and orientations should be clearly marked so that they are visible through the resin.

Initial cutting of the sample is done on a large offcut saw using oil as the blade lubricant to prevent the swelling of the clays in the sample. Despite the care with which the sample was impregnated; the degree of impregnation depends greatly on the permeability

of the sample. It is commonly found that the impregnation of very compact material is only a rind several cm thick around the sample and that the center of the sample is only partially impregnated. For this reason the first cuts should be located in the outer part of the block. The offcut blocks should be approx. 1cm thick. Once the blocks are cut they should be immediately labelled and oriented. After the first cutting the blocks are cut to size on the small offcut saw and cleaned using petroleum ether to remove the oil. Other solvents such as acetone may cause softening and dissolution of the resin.

If the offcut block obtained is poorly impregnated it can be reimpregnated or surface impregnated. Epotek 301 Bonding Epoxy is used surface impregnate the small block. The block is placed in a small vacuum chamber and the resin is poured over it. Then it is placed under vacuum until the resin has infiltrated the sample. The block is then wiped clean of excess resin and a plastic sheet is placed on top of the block and the resin is left to harden. A weight is placed on top of the block to produce a smooth surface. To reimpregnate using 3M resin the initial procedure is repeated. Once the block is satisfactorily impregnated it is trimmed to a 3 X 2 cm size for the initial steps in production of the thin section.

To make the thin section the block is first polished on the logitech automatic thin section machine using 16 micron grit in oil. Then it is polished using 9 micron grit in oil until the surface to be bonded is mirror smooth. After polishing the block is placed into a beaker of petroleum ether in a sonic bath for 10 minutes to remove any traces of oil (all the oil must be removed or the block will imperfectly bond to the glass slide and loss of the thin section during the final stages of thin section production). Following cleaning, the block is bonded to a frosted glass slide using Epotek Bonding Resin and a logitech bonding jig. After drying for three days the bonded block is cut to 150 microns thickness using the vacuum slide holder on a large offcut saw. The offcut should be retained in case the first slide does not work. The thick slide is then ground to approx. 75 microns thickness on the surface grinder advancing the slide into the grinding wheel at a rate of 1 degree for each pass of the grinder.

The slide is then mounted on a logitech slide producer and polished using 16 micron grit in oil until the slide is 40 microns thick. Then using 9 micron grit the slide is polished until it reaches the optimum thickness of 25 -30 microns. This final polishing stage is

difficult as it is at this stage that the thin section may be destroyed by plucking. If plucking begins it is advisable to stop polishing at that point rather than lose the section. The slide is labelled and a coverslip is placed over the finished section.

Experimentation with a polyester resin, an experimental gamma-ray hardening resin, ardalite resin, and 3M casting resin showed that 3M casting resin gave the best results in regard to: cost, availability, ease of handling the resin, and compatibility with the bonding resin. Polyester resin was too viscous giving poorer impregnations and outgassed for a long period of time indicating that curing was slow. The gamma-ray resin gave good impregnation results but was not as compatible with the bonding resin resulting in more plucking. This resin also experienced shrinkage upon curing, and was very expensive.

APPENDIX 3: METHOD USED FOR PEBBLE LITHOLOGY ANALYSIS

Pebble samples were analyzed to detect changes in pebble lithologies upwards through the section. Variations in pebble lithology may indicate changes in the process of deposition or changes in source. Shaw (1979) in his investigation of the Sveg till noted that the till was composed of two units, a lower massive diamicton overlain by a diamicton which was intercalated with sand laminae. In the lower massive diamicton local clasts predominated while in the upper stratified diamicton non-local clasts were more predominant. In the Diamicton-Glaciolacustrine Association the most common sequence begins with the unstratified diamicton (Facies 6) overlain by the intercalated diamicton and sand laminae (Facies 8). To determine if there is any change in pebble lithology similar to that observed by Shaw (1979) in the Sveg Till sections between these two facies, pebble lithology analysis was done. The method used for the analysis is that of Shetson (1983, 1985). Using this method Shetson has been able to differentiate the deposits of different ice lobes in Alberta.

METHOD OF ANALYSIS

The method requires the collection of pebble samples which can be divided into two fractions, a coarse fraction > 1.5-2cm in size and a fine fraction < 1.5-2cm in size. Once the sample has been divided into coarse and fine fractions the lithologies of the clasts are identified and grouped into 6 major categories;

4. Igneous and metamorphics (IM),
5. Eastern carbonates (EC),
6. Metaquartzites (MQ),
7. Quartzites (QT),
8. Western carbonates (WC),
9. Local bedrock (LB).

This data is compiled in Table A3.1.

Table A3.1 Table of Pebble Lithology Samples from the New Pit West and the Riverbend 1 Section.

IM- Igneous and metamorphic clasts

EC- Eastern derived carbonates

MQ- Metaquartzites, western derived

QT- Quartzites, western derived

WC- Western derived carbonates

LB- local bedrock

each category is divided into clasts <1.5 cm,

>1.5 cm, and the total number of clasts in the category.

Table A3.1 Pebble Lithologies

Sample	IM	EC	MQ	QT	WC	LB	Total														
	<1.5>1.5	Co. <1.5>1.5	Co. <1.5>1.5	Co. <1.5>1.5	Co. <1.5>1.5	Co. <1.5>1.5	Co. <1.5>1.5														
PS1	48	7	55	9	5	14	3	3	6	30	21	51	1	0	1	19	10	29	109	46	155
PS2	4	4	8	3	3	6	3	2	5	22	52	74	4	4	8	6	5	11	42	70	112
PS3	41	8	49	2	3	5	3	0	3	21	19	40	4	3	7	11	19	20	82	42	124
PS4	35	9	44	6	0	6	4	6	10	34	23	57	2	6	8	12	4	16	93	48	141
PS5	25	9	34	8	0	8	6	7	13	26	24	50	3	4	7	12	3	15	69	48	117
PS6	23	13	36	9	4	13	2	3	5	19	20	39	3	5	8	6	10	16	63	55	118
PS8	36	15	51	17	3	20	4	7	11	36	23	59	10	2	12	12	3	15	53	116	169
PS9	32	18	50	12	7	19	5	4	9	25	27	52	6	8	14	9	1	10	89	65	154
PS10	5	11	16	3	2	5	0	3	3	12	13	25	0	0	0	30	19	49	43	50	93
PS11	15	15	30	14	3	17	2	7	9	18	10	28	0	0	0	17	8	25	66	43	99
RB1	157	14	171	72	7	79	24	3	27	98	19	117	19	4	23	28	6	34	398	53	451
RB2	104	14	118	37	5	42	7	5	12	58	24	82	17	4	21	27	2	29	239	54	293
RB3	88	26	114	47	8	55	11	3	14	52	19	71	4	26	30	10	5	15	283	64	347
RB4	35	19	54	17	12	29	3	1	4	21	18	39	9	10	19	5	3	8	90	63	153

From this data various indices are calculated. The first indice to be calculated is the Dilution Factor (Rd). Using the formula:

$$Rd = \frac{N(Qc) \times N(ERc)}{N(Qf) \times N(ERc)}$$

1. Qc=coarse metaquartzite + orthoquartzite
2. Qf=fine metaquartzite + orthoquartzite
3. ERc=coarse eastern derived igneous and metamorphic clasts + Eastern carbonates
4. ERf=fine eastern derived igneous and metamorphics + Eastern carbonates

If the sample has been diluted by local bedrock clasts the Rd value will be >1.5. Undiluted samples have Rd values <1.5. The Rd values for the pebble samples are tabulated in Table A3.2.

Once the dilution indice has been calculated the Pebble Lithology Indice (Rs) is calculated. If the sample is diluted the formula:

$$Rs = \frac{(IM + 1.5EC + 0.33MQ)n}{(N - LB)}$$

1. IM=igneous and metamorphics.
2. EC=eastern carbonates.
3. MQ=metaquartzites.
4. LB=local bedrock.
5. n=total number of clasts in the coarse or fine fraction.
6. N=total number of clasts in the coarse and fine fractions.

If the sample is non-diluted the formula used is:

$$Rs = \frac{IM + 1.5 EC}{(N - LB) - 1.47MQ}$$

Table A3.2 Pebble lithology indices calculated for facies 6, 8, and 9 in the
New Pit West and Riverbend 1 sections.

Rd- dilution indice for the clasts

Rsf- Pebble Lithology Indice for the $<1.5\text{cm}$ fraction

Rsc- Pebble Lithology Indice for the $>1.5\text{cm}$ fraction

Rsc- Pebble Lithology Indice for the combined fractions

Table A3.2 Pebble Lithology Indices

Sample	Rd	Rsf	Rsc	Rscor.
NPWPS1	3.39	.69	.43	.64
NPWPS2	2.16	.26	.14	.185
NPWPS3	3.1	.63	.38	.55
NPWPS4	3.48	.56	.25	.45
NPWPS5	2.26	.71	.25	.49
NPWPS6	1.91	.66	.44	.56
NPWPS8	2.15	.60	.44	.55
NPWPS9	1.4	.69	.49	.60
NPWPS10	1.33	.48	.42	.44
NPWPS11	2.73	.94	.62	.80
RBPS1	1.99	.74	.54	.72
RBPS2	2.00	.76	.44	.70
RBPS3	1.70	.59	.66	.60
RBPS4	1.99	.74	.54	.72

These calculations can be performed for the coarse and fine fractions and for the combined fractions. The indices calculated from the pebble lithology data is compiled in Table A3.2.

The calculated indices were then plotted on graph paper according to their vertical distance from the base of the sections. This plot is shown in Figure A3.1.

Figure A3.1 Indices calculated from pebble lithology samples from the New Pit West and Riverbend 1 Sections, plotted at their sampling locations in the sections, illustrating the uniformity of the pebble lithologies upwards through Facies 6, 8, and 9. The large deviation at the base of the New Pit West section is due to contamination from the underlying pre-glacial sands and gravels.

